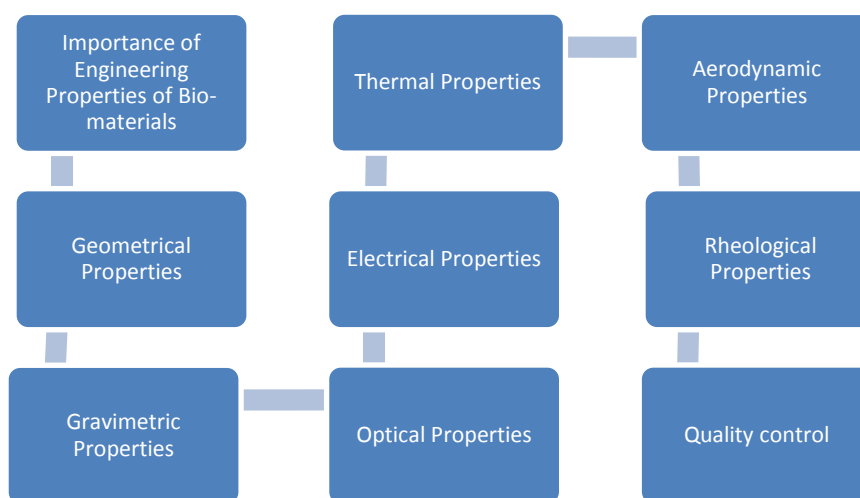


ENGINEERING PROPERTIES OF BIO-MATERIALS AE 602

Course objective:

- To acquaint and equip the students with different techniques of measurement of engineering properties and their importance in the design of processing and material handling equipments.
- To acquaint and equip the students with the latest standards to maintain food quality as well as to study Hazard Analysis Critical Control Point (HACCP) protocol.

Course:



Practical

| S. N. | Name of the experiment | Hours |
|-------|---|-------|
| 1 | Determination of shape and size of Grains, fruits and vegetables | 2 |
| 2 | Determination of Particle density/True density, Bulk Density porosity and Specific Gravity of Food Grains | 2 |
| 3 | Determination of Angle of Ripose and Coefficient of Internal and External Friction for Food Grains | 2 |
| 4 | To study the separation behaviour of a grain sample in a vertical wind tunnel (Aspirator column) | 2 |
| 5 | Determination of Stress-Strain Behaviour of Different Food Grains | 2 |
| 6 | Determination of Thermal Conductivity of Different Food Grains | 2 |
| 7 | Determination of Thermal Diffusivity of Different Food Grains | 2 |
| 8 | Determination of Specific Heat of Food Grains | 2 |
| 9 | Determination of Electrical Conductivity of Liquid Food Materials | 2 |
| 10 | Detection of adulteration in food products viz. milk, ghee, honey etc. | 2 |
| Total | | 20 |

Reference:

1. Mohesenin N.N. 1980. *Physical Properties of Plant and Animal Materials*. Gordon & Breach Science Publ.
2. Mohesenin NN. 1980. *Thermal Properties of Foods and Agricultural Materials*. Gordon & Breach Science Publ.
3. Peleg M & Bagelay EB. 1983. *Physical Properties of Foods*. AVI Publ. Co.
4. Rao M.A. & Rizvi S.S.H. (Eds.). 1986. *Engineering Properties of Foods*. Marcel Dekker.
5. Singhal OP & Samuel DVK. 2003. *Engineering Properties of Biological Materials*. Saroj Prakashan.
6. Hallstrom B, Meffert HF, Th Spesis WEL & Vos G. 1983. *Physical Properties of Food*. Elsevier.
7. Ronal Jowitt, Felix Escher, Bengt Hallsrram, Hans F, Th. Meffert, Walter EC Spices & Gilbert Vox. 1983. *Physical Properties of Foods*. Applied Science Publ.

Evaluation Scheme

The questions will cover all the chapters of the syllabus. The evaluation scheme will be as indicated in the table below

| Chapter | Hours | Marks Distribution* |
|--------------|-----------|---------------------|
| 1 | 2 | 8 |
| 2 | 4 | |
| 3 | 3 | 8 |
| 4 | 2 | |
| 5 | 3 | 4 |
| 6 | 3 | 4 |
| 7 | 3 | 4 |
| 8 | 5 | 12 |
| 9 | 5 | |
| Total | 30 | 40 |

*There may be minor variation in marks distribution

➤ The questions setting should be in the multiplication of either 8 or 10.

Chapter-1: IMPORTANCE OF ENGINEERING PROPERTIES OF BIO-MATERIALS

- The use of various devices and techniques in handling and processing of plants and animals has increased the importance of the knowledge of basic engineering properties of biomaterials.
- Engineering properties of Biomaterials is the attributes that affect the handling and processing of biomaterials.
- The handling and processing can be done by various means such as mechanical, thermal, electrical, optical and some sonic techniques and devices.
- The knowledge of various properties of biomaterials is very important in:
 - ✓ In the design of machines, structure, processes and controls,
 - ✓ Analyzing and determining the efficiency of a machine or an operation,
 - ✓ In developing new consumer products of plant and animal origins, and
 - ✓ In evaluating and retaining the quality of the products.

Various Properties of Biomaterials and their Engineering Use:

1. Physical Properties:

| | | | |
|--------------|------------------|-------------------|--------|
| Shape | Size | Weight | Volume |
| Surface area | Density | Porosity | Color |
| Appearance | Drag Coefficient | Centre of Gravity | |

- The importance is associated with:
 - Design of a particular machine or
 - Analyze of Behavior of products during process.
- The importance of:
 - Shape and size of grain: screening for optimum separation and unit operations.
 - Volume and Surface area of grain and food materials: the packaging and processing of materials.
 - Bulk density, specific density and porosity: Handling the material for filling in bags and storage.
 - Also help in calculating thermal diffusivity in heat transfer problems in hydraulic and pneumatic conveying of materials.
 - Color: most valuable techniques as light reflectance for selective separation in field as well as I processing plant to remove undesirable off colored material from the produce.

2. Mechanical properties:

| | | | |
|------------------|----------------------|-------------------------|--------------------------|
| Hardness | Compressive Strength | Tensile Strength | Impact Resistance |
| Shear Resistance | Compressibility | Coefficient of Friction | Coefficient of Expansion |
| Elasticity | Plasticity | Aerodynamic Properties | Hydrodynamic Properties |

- The importance of these characteristics is associated with the prevention of grains and food materials from damage which occurs in harvesting, threshing and transportation.
- The mechanical damage to seeds and grains can seriously affect the viability and germination power. Moreover, the damage site may act as the site for microbial and fungal attack.
- The importance of mechanical properties such as hardness and impact resistance can be justified while milling, other unit operations such as size reduction and transportation and also in design of machines.
- Coefficient of friction is important for engineers and designers for designing and predicting the motion of materials in handling and harvesting, pressure of grain and silage against the bin walls and silos.

- Aerodynamic and hydrodynamic properties are needed for air and water conveying and separation of materials.

3. Optical Properties:

| | | |
|---------------------|-------------------|-------------------|
| Light transmittance | Light reflectance | Light absorptance |
| Color | Contrast | Intensity |

- It includes light transmittance, reflectance, absorptance, contrast, intensity etc.
- Light transmittance and reflectance properties of agri materials are extremely useful for electronic sorting and grading, maturity and surface color determination.
- It is also importance in various handling and processing activities like:
 - ✓ Internal color of tomatoes
 - ✓ Fruit maturity
 - ✓ Blood spots in eggs
 - ✓ Internal damages

4. Thermal Properties:

| | | | |
|---------------------|------------------|---------------------|----------------------|
| Specific heat | Thermal capacity | Thermal diffusivity | Thermal conductivity |
| Surface conductance | Absorptivity | Emissivity | Transmissivity |

- It includes thermal diffusivity, thermal conductivity, specific heat etc.
- Many agri products of plants and animals origin are subjected to various types of thermal processing before they are placed at access to consumers.
- Process are heating, cooling, drying and freezing.
- Knowledge is essential for design of equipment and prediction of process time.
- During thermal treatment of biological materials, time and temperature are equally important to preserve the viability, nutrients and quality of materials.

5. Electrical Properties:

| | | |
|-----------------------|------------------------------------|---|
| Conductance | Resistance | Capacitance |
| Dielectric properties | Reaction electromagnetic radiation | Conductivity ability of seeds to hold a surface charge. |

- It includes electrical conductance, capacitance, dielectric properties etc.
- Electrical conductance and capacitance properties have been used in moisture content determination.
- Dielectric losses when placed in electro dynamic field have been used in drying of agri products.

Physical Properties and Characteristics:

- The characteristics of a food materials that are independent of the observer, measurable, can be quantified and define the state of the material are considered as its physical properties.
- It describes the unique, characteristic way a food material responds to physical treatments involving mechanical, thermal, electrical, optical, sonic and electromagnetic process.
- The determination of physical characteristics of agricultural products is much important because of their irregular shape and variability in size.
- Knowledge of a food's physical properties is necessary for:
 - Defining and quantifying a description of the food material.
 - Providing basic data for food engineering and unit operations, and
 - Predicting behavior of new food materials.
- Physical properties are divided into:
 1. Gravimetric Properties and
 2. Geometric Properties.

Chapter-2: Geometric Properties

- Geometric Properties includes:
 - I. Size
 - II. Shape
 - III. Surface Area
 - IV. Volume
 - V. Appearance, etc.
- The importance of this characteristics is associated with:
 - The design of a particular machine
 - Analysis of the behavior of the product during a process.
- Properties, Importance and Measurements in basis of:
 1. Shape and Size
 2. Roundness
 3. Sphericity
 4. Average Projected area and Volume

1. Shape and Size:

4. Average Projected Area:

- Houston(1957) proposed a new criterion of size, defined as the average of the projected areas takes along three mutually perpendicular axes.
- This criterion, was referred as Criterion Area “Ac”.
- Used for Irregular shaped agricultural products.
- The projected areas along with three perpendicular axes are taken and the Arithmetic Mean of these areas is calculated.
- The average size of the particles is determined from the criterion area,

$$Ac = (A_1 + A_2 + A_3)/3$$
 Where A₁, A₂ and A₃ are the projected area in three mutually perpendicular directions.
- This method is suitable for size determination of vegetables and fruits like tomato, carrot, apples, etc.
- It is time consuming as projected area of individual samples is to be determined.
- It may also be successfully used for small grains like sorghum and millet seeds.

FIGURE Attache

To test the validity of this criterion, a relation was developed between the true average projected area “A” and the volume of object “V”.

Based on the theories of convex bodies(Bannesen & Frenchel, 1948), it has been established that

Where V is the volume and S is the surface area of the convex body. It has been shown that the average projected area of a convex body is one-fourth the surface area(polya and Szega, 1951).

Substituting $S=4A$ in the above equation,

Where, k is constant

For a sphere where equality is achieved, $k = \dots\dots\dots = 1.21$

$k=1.76$, for carrot
 $k=1.36$ for potatoes
 $k= 1.24$ for lemon.

5. Resemblance to geometric bodies:

In some cases the shape can be approximated by one of the following geometric shapes:

- Prolate Spheroid: Formed when an ellipse rotates about its major axis
- Oblate Spheroid: Formed when an ellipse rotates about its major axis.
- Right Circular cone

FORMULA.....

Where, a and b are respectively major and minor semi-axis of the ellipse of rotation and e is eccentricity given by:

Formula.....

Where, r_1 and r_2 are the radii of base and top, h is the height of frustum.

Surface Area:

- The knowledge of surface area of some part of plant materials like leaf and fruits is important to plant scientists as well as engineers for handling and processing of the products.
- To determine the application rates of insecticides and fungicides use, transpiration rates, heat transfer rate, surface area is very important.
- Crops like tobacco and tea, where leaf is the major commercial product, leaf area is a good indicator of yield potential
- Leaf surface area is measured by following methods:
 - Graphical Method
 - Air flow planimeter

Surface Area of few Biomaterials:

Apple, $S=6.72+0.129W$

Pears, $S= 7.49+0.99W$

Plums, $S= 2.18+0.149W$

Egg= $4.82W^{\text{power } 0.66}$

Chapter-3: Gravimetric Properties

- Gravimetric properties like density, specific gravity, porosity etc. are very important physical properties.
- They have their own importance during the handling of material for filling in bags and storage.
- Variation in grain densities tends to cause undesirable stratification as bags or bins when filled.
- The irregular shape and porous nature of some agricultural materials present a number of problems in volume and density measurement.
- Information on these physical properties is of great help in calculating thermal diffusivity in heat transfer problems, in determining the value of Reynold's number in hydraulic and pneumatic conveying of material.

1. Porosity:

- It is an important property of agricultural product. The porosity may be defined as relationship between volumes of inter-grain space to the total volume of grain mass.
- The porosity can be determined by the relationship between the true density and bulk density of the material as follow,

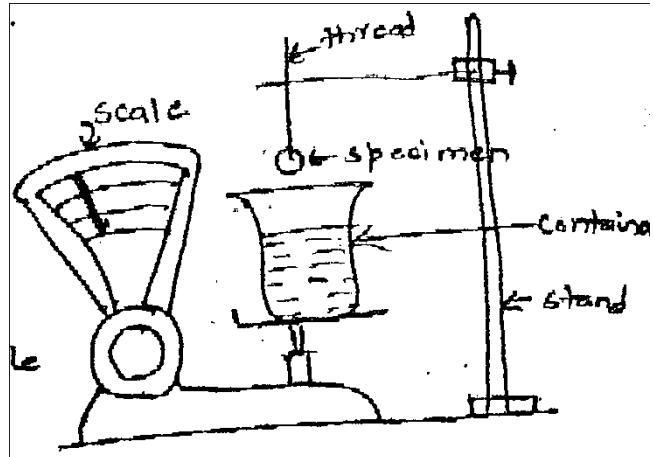
$$P = 1 - (\rho_b / \rho_g)$$
 Where, ρ_b = bulk density of material.
 ρ_g = True density of material.
 - The bulk density of material is obtained by the test weight device.
 - The true volume of the sample is determined with the pycnometer and then the amount of grain is weighed to determine the true density.
- Porosity allows gases, such as air and liquids to flow through a mass of particles referred to as packed bed in drying and distillation operations.
- Beds with low porosity are more resistant to fluid flow and thus are more difficult to dry, cool or heat.
- With high porosity, air flows easily through bed, drying is fast and the power requirement by fans and pumps are low.

Volume and Density:

- The density and specific gravity of grains play an important role in design of storage bins, separation of desirable materials from impurities, cleaning & grading, evaluation of the grain maturity, texture & softness of fruits and quality evaluation of products such as peas, sweet corn, potatoes which increase in their density as they mature are some of the examples where density or specific gravity of the materials has good applications.
- The irregular shape of most agricultural products, the small size of the materials such as seed and grains and the porous nature of others such as feed pellets and wafers present certain problems in volume and density measurement because of the irregular shape of the product, volume is usually determined by water displacement.

(1) Platform scale

- It is a simple technique which is applied for large objects such as fruits and vegetables.
- The fruit is first weighed on the scale in air and then forced into water by means of thread and stand. The second reading of the scale with the fruit submerged minus the weight of the container and water is the weight of the displaced water.



Volume(m³)= weight of displaced water(kg)/weight density of water(kg/m³)

Weight density(kg/m³) = wt. of material in air(kg)/ volume of material(m³)

Therefore,

Sp. Gravity = wt. density of fruit/ wt. density of water
= (wt. in air *sp.gr of water)/ wt. of displaced water.

(2) Specific gravity Gradient Tube:

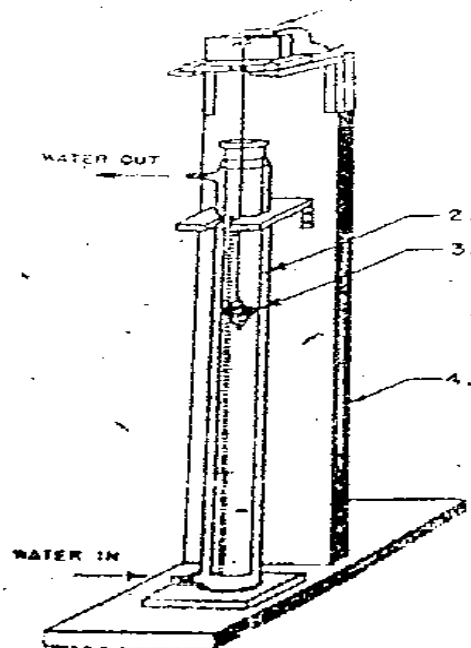


Figure 3.9 Specific gravity gradient column for small seeds, grains and other solids (1. water inlet, 2. water jacket, 3. elevating basket, 4. stand)

- A fast and accurate method for determining volume and weight density of agricultural products is the use of specific gravity gradient tube.
- The technique is based on observing the level to which a test specimen sinks in liquid column exhibiting a density gradient in comparisons with standard glass floats.

- The only requirement is that the specimen must be impervious to the liquid in the column until the liquid and test specimen have reached equilibrium and reading is obtained.
- In conducting the specific gravity test, the specimen is placed gently in the tube allowing the liquid and specimen to reach equilibrium.
- At this time, the height of the specimen in the tube is read and by reference to the calibration curve, the sp. gravity is determined.
- If equilibrium is not obtained, the liquid may be penetrating the specimen.
- If calibration chart is not available, a method of interpolation can be used employing the following expression:

$$sp. gr at x = a + \frac{(x - y)(b - a)}{(z - y)}$$

Where,

a & b= sp.gravities of two standard floats(known).

y & z= distⁿ of the two standard floats a & b, bracketing the unknown, respectively, measured from a reference level.

x= distance of unknown from the same reference level.

- A wire screen basket attached to a long wire and an electric clock motor forms an elevator for removing the old specimen from the tube at such a slow rate so that the gradient is not disturbed.
- The accuracy of the technique depends on gradient of sp. Gr of the liquid/mm height of column.

Chapter-4 Optical Properties

Light is probably the most useful form of energy of gaining information about a material. Vision of course, is the primary methods of using light for this purpose. To understand how light interacts with a material, one should have the knowledge of light propagation, physical law and the light spectrum. The properties related to the behaviour of the light with biological materials is known as optical properties.

Optical behaviour using light transmittance and reflection techniques have been explored in recent years of electronic sorting and grading, maturity prediction and surface colour determinations. Hidden infestations and mechanical damage of fruit and vegetables have successfully been detected by using specialized optical techniques.

I. Colour:

- Colour in food is usually due to presence of natural pigments such as anthocyanins, carotenoids and chlorophyll which not only helps to determine quality, it can also tell us many things.
- Colour is commonly an indicator of ripening or spoilage.
- Potatoes darken in colour as they are fried and we judge the endpoint of frying by colour. The surface colour of chocolate is due to its storage history.
- These and much other type of colour changes can accurately measured in laboratory and in the plants which influence or reflect food quality.
- If food is a transparent liquid such as wine , beer or grapes juice or if a colored extract can be obtained from the food, then various types of colorimeter or spectrophotometers can be used for colour measurement.
- With these instruments, a tube of liquid is placed in a slot and light of reflected wave length is passed through the tube.
- This light will be observed depending on the colour of liquid and the intensity of colour. Two liquids of exactly the same colour and intensity will transmit equal fractions of light directed through them.
- If one of the liquid is jam and other is the same juice somewhat diluted with water, the later sample will transmit a greater fraction of the incoming light and this will cause a proportionately greater response on the instrument.
- Such instrument can also measure the clarity or cloudiness of liquid depending on the amount of light passing through the liquid.
- Colour measurement can further quantified. Light reflected from a coloured object can be divided into three components, which have termed a value, hue and chroma.
 - Value refers to the lightness or darkness of the colour or the amount of white or black.
 - Hue refers to the predominant wavelength reflected, which determines what the perceived colour is red, green, blue etc.
 - Chroma refers to the intensity strength of the colour.

II. Gloss:

- Gloss is the name given to light specularly reflected from a plain smooth surface.
- It can be defined by a curve, which represents the intensity of light reflected at the surface at different angles of incidence and viewing.
- Gloss is important to the attractiveness of gelatin desserts, buttered vegetables.
- It is measured by glossmeters. It measure the intensity of light reflected at the three angle of incidence and reflection , and normally give results in the form of indices,

obtained by comparing the sample reflectance to that a highly reflective flat glass, used as a calibration standard.

- Glossiness of a product is a property of the smoothness of its surface.
- When this characteristics is desired, manufacturers try to improve it , as in the case of fruits covered with wax to make them more visually appealing.

Applications

- Sorting of fruits by Delayed Light Emission (DLE)

The delayed Light Emission is based on the principle that some fruits emit light several second after excitation by a light source. Majority of green chlorophyll containing fruits have this property. The duration and intensity of the DLE can be related to chlorophyll concentration or apparent greenness thus providing a basis for sorting.

The broad activation spectrum which produces DLE from intact green fruit is given in the figure. The visible spectrum peak is about $680\text{ m}\mu$ (red color) but the fruit reserves significant excitation over a range of about $625\text{-}725\text{ m}\mu$. Important for practical purposes since readily available light sources produce good output in this range. Day light, incandescent and fluorescent lamps and some flash lamps can be used to produce such lights.

A conveniently observe property of DLE is that beyond its saturation level additional illumination has little effect in producing an increase in DLE intensity. The green peaches and other fruit like tomatoes, Guava etc show that emitted 2 seconds after saturation the emission energy is the order of 10^{-8} watt/cm^2 of surfaced for very green specimens and 10^{12} watt/cm^2 nearly ripe ones. A photo tube having red response is used as a suitable detector. A suitable electronic circuit can be used to measure DLE.

This device uses on excitation source (room light or lamp) to subject the specimen to excitation. Then they enter a dark tunnel and the DLE decays. A delay of 5-10 seconds between excitation and measurement is selected from the DLE characteristics curve. The delay period is controlled by the length and speed of the convey of the specimen are carried single file past on photo tube which produces a signal according to the strength of the DLE. The signal activates the mechanical selector, a solenoid actuating a deflecting vane. The level at which the selector is activated can be adjusted to provide splitting the fruit low at a desired stage of maturity. Successful separations into more than two grades can be achieved by rerunning one grade after readjusting the split point. This device has very little influence of temperature changes. The device can be used for the fruits insists and very useful for sorting fruits like lemons, tomatoes, peaches and guava etc.

- Sorting by reflectance method

Many biological materials such as peas, beans, tomatoes and apples differ in between varieties, stage of maturity and extent of damage. These can be sorted electronic colour sorter. The machine can separate such seeds by differences in colour and also removes mudballs and discoloured seeds in the same operations.

The construction and working of machine is shown in the figure. The electronic colour sorter views each seed individually with photoelectric cells. The seed is compared with a selected background or colour range and is discharged from the machine according to its colour. If the colour of the object is of the desired colour it is sorted. If the shade falls within the rejected range, a blast of compressed air deflects the seed and sends it into the reject discharge spout.

Fig: Flow diagram of the separating unit of the sortex G-3S Electronic colour sorters. Electronic colour sorters are highly sensitive machine and must be operated and maintained by trained personnel. Since the machines are high, but operating costs are generally low. The usefulness of these machines is greater with vegetables and fruits like sorting of overripened tomatoes, sorting of damaged eggs, sorting of red apples from green ones etc.

- Sorting of materials by transmittance method

The light transmission characteristics of different fruits can be effectively used for grading and sorting them when light is incident on any material, only a fraction of it is transmitted through the material, the amount depending on the optical density of the material. If I is the intensity of the incident wave and I_t is the transmittance wave through x being the thickness of the material then according to Lamberts Law.

$$I_t = I e^{-kx}$$

Where K is the absorption coefficient. Optical is defined as

$$O.D. = \log \frac{I}{I_t} = kx \log 10^e$$

Optical density is also dependent on the wave length of the incident light beam.

Optical density is thus independent of thickness of the material. The ratios of optical density at different wavelengths can be used to grade different types of fruits and food material like tomatoes, eggs, etc.

Chapter - 5. Electrical Properties

The knowledge of electrical properties of agricultural materials has become increasingly important with the more sophistication of agricultural production and processing technology. The new uses for electric energy are developed and new methods, processes, and devices are coming into existence which utilize or are influenced by the electrical nature of the materials. The area of electrical properties is a board subject matter field even when limited to agricultural products. An attempt is made to review the scope of electrical properties of biomaterials and their significance in different processes.

There are two main electrical properties in food engineering: Electrical Conductivity and Electrical Permittivity. Electrical properties are important when processing foods involving electric fields, electric current condition or heating through electromagnetic waves. These properties are also useful in the detection of processing conditions or the quality of foods.

1. Electrical Conductivity:

It is a measure of how well electric current flows through a food of unit cross-sectional area A, unit length L, and resistance R. It is the inverse value of electrical resistivity (measure of resistance to electric flow) and is expressed in SI units S/m. it is denoted as σ .

$$\sigma = L / A.R$$

The electrical conductivity of foods has been found to increase with temperature (linearly) , and with water and ionic content. Mathematical relationships have been developed to predict the electrical conductivity of foods materials: for example, for modeling heating rates through electrical conductivity measurements, or for probability distribution of conductivity through liquid particle mixtures and helps in moisture determination. At freezing temperatures, electrical conductivity increases with temperature, as ice conducts less well than water. Starch transitions and cell structural changes affect electrical conductivity, and fat content decreases conductivity.

2. Electrical Permittivity:

It is a dielectric property used to explain interactions of foods with electric fields. It is the measure of how much resistance is encountered when forming an electric field in a medium. It determines the interaction of electromagnetic waves with matter and defines the charge density under an electric field. In solids, liquids and gases the permittivity depends on two values ϵ' and ϵ'' . The complex permittivity is conveniently expressed as:

$$\epsilon = \epsilon' - i\epsilon''$$

Where ϵ' = dielectric constant, related to capacitance of a substance and its ability to store electrical energy;

ϵ'' = dielectric loss factor, related to energy losses when the food is subjected to an alternating electrical field (i.e. Dielectric relaxation and ionic conduction.)

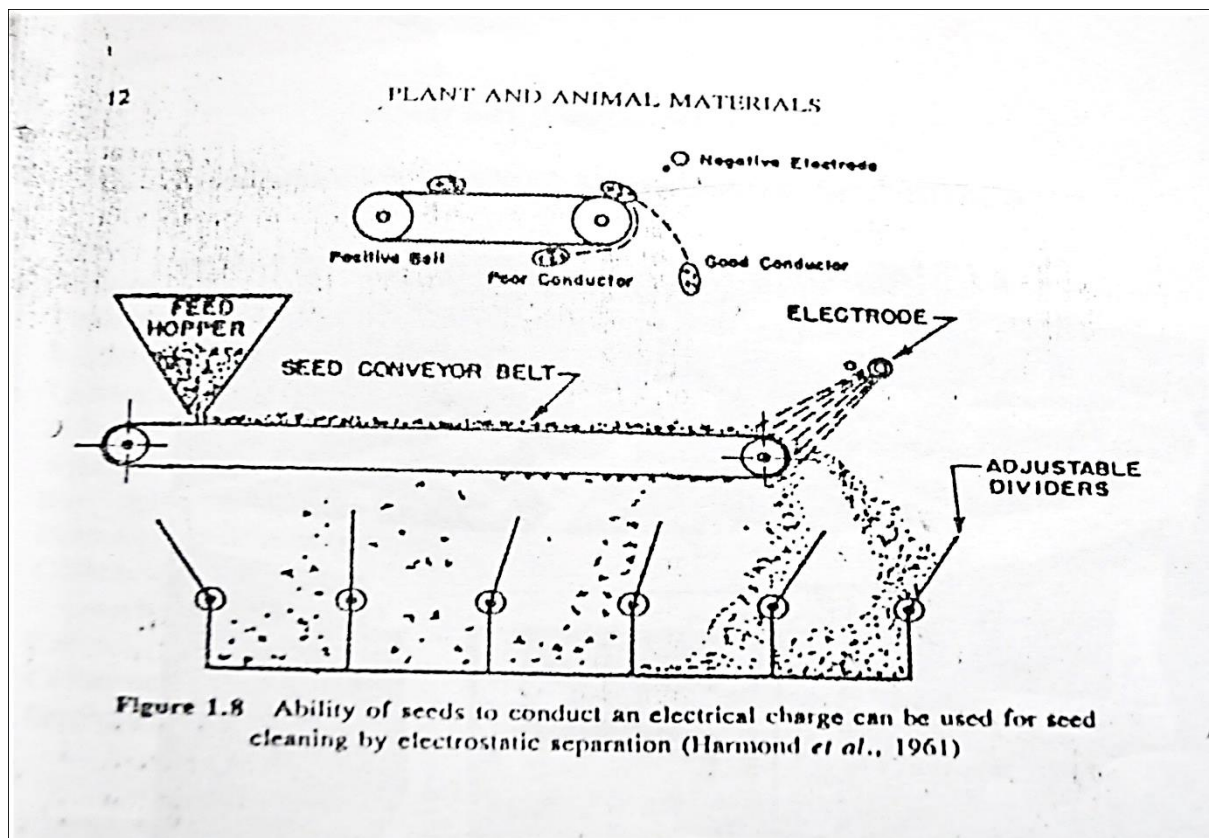
Applications:

- Conductivity plays a fundamental role in ohmic heating in which electricity is transformed to thermal energy when an alternating current flow through food.
- Electrical conductivity can be used for acidity studies, therefore, and for monitoring processes where acidity increases, as in fermentations.

- Crystallization processes (for example, in sugar solutions) can be monitored with conductivity measurements as conductivity has been found inversely proportional to viscosity, which in turn follows super saturation closely.
- Conductivity measurements have also been used to measure moisture contents of materials, particularly grain products.
- Dielectric properties are important in the selection of proper packaging materials and cooking utensils, and in the design of microwaves and radio frequency heating equipment, because they describe how the material interacts with electromagnetic radiation.

Electrostatic separation of seeds and foreign matters:

- This method of seed separation can be used to separate seeds of different electrical properties essentially independent of differences in size, shape, weight or surface texture.
- It separates seeds by allowing them to fall free in space and then using an electric field to deflect some seed from the normal flight path.
 - The electrostatic separator is made up of feed hopper, a moving feed belt or revolving feed drum, a high voltage supply, an electrode and several adjustable dividers which separate the different discharge spouts.
 - The feed hopper meters in thin layers of seeds onto the feed drum or belt. The feed drum or belt moves seed through an electric field created by the electrode. The seed then fall toward discharge spouts below the adjustable dividers.
- When the seed pass through the electrical field, they all have an opportunity to become charged.
- A given seed however, tends to hold or lose a charge according to its individual electrical conductivity.
- The good conducting seed will lose its charge readily, while the poor conducting seed holds its charge longer.
- Conductivity thus can be used to separate the different types of seeds.



Chapter – 6 Thermal Properties

Many of the agricultural products of plant or animal origin are subjected to various types of thermal processing before they are placed at the access of the consumer. The thermal processing may include heating, cooling, drying and freezing. It is upon the thermal properties of the product that any change of temperature will largely depend.

Heating or cooling agricultural products may be accomplished by the methods of convection, conduction and radiation. Knowledge of such thermal characteristics as specific heat, thermal conductivity and thermal diffusivity is essential for design of equipment and prediction of process time. The knowledge of thermal properties is also essential for researchers and designers in the field of food technology for a variety of purposes e.g. predicting the drying rate or temperature distribution within foods of various composition and geometric shapes when subjected to different drying, heating and cooling processes or to allow optimum design of heat transfer equipment dehydrating and sterilizing apparatus.

Applications:

- Heat treatment of cereals and some of the pulses has shown some promise in stimulating germination.
- The fungus causing decay of onions in storage vanishes in the temperature range of 40-60°C.
- The heat treatment is also used for thermal killing of insects, pest in storage of cereals like wheat, maize in recent years.
- In fruits and vegetables the enzymes and microorganism causing deterioration can be controlled by low temperature. It is said that fresh produce deteriorate as much in an hour at 90°F as in a day at 50°F, or in a week at 32°F.
- Hard seeds of red clove can be made permeable by application of properly regulated heat. Heating of these seeds for 4 min at 200°F can reduce the number of hard seeds by as much as 80%.
-

Fourier's Law of Heat Conduction

We need a driving force to overcome a resistance in order to transfer a property. For any kind of molecular transport processes (momentum, heat or thermal energy, and mass) the general equation can be written as follows:

$$\text{Rate of a transfer process} = \frac{\text{Driving force}}{\text{Resistance}}$$

[3.1]

Consider a wall of thickness X and surface area A . imagine that the wall is initially uniform at a temperature T_0 . At time $t=0$, one side of the wall is suddenly brought to a slightly higher temperature T_1 and maintained at that temperature. Heat is conducted through the wall as a result of the temperature difference and as time proceeds, the temperature profile in the wall changes. Finally, linear steady-state temperature distribution is achieved as shown in Fig.3.1. The driving force for the heat transfer to occur is the temperature difference:

$$\text{Driving force} = T_1 - T_0$$

[3.2]

While the rate of heat conduction through the wall is proportional to the heat transfer area (A). the thickness of the wall (X) provides resistance to heat transfer. In addition, the ability of the wall material to conduct heat should be considered. Each material has a different ability to conduct heat. The responses of steel and wood to heating are not the same when they are exposed to the same amount of heat. This material property is name thermal conductivity (k). considering all these parameters the resistance to heat transfer can be written as:

$$\text{Resistance} = \frac{X}{kA}$$

[3.3]

When the steady-state condition has been reached, the rate of heat flow () through the wall can be written by substituting Eqs. (3.2) and (3.3) into Eq. (3.1):

Equation (3.4) in differential form gives Fourier's law of heat conduction:

Specific heat

It is defined as the amount of heat in kilocalories that must be added to or removed from 1kg of a substance to change its temperature by 1°C. the specific heat of wet agricultural material is the sum of specific heats of bone dry material and its moisture content. If C_d and C_w are the specific heats of bone dry materials and water respectively, and m is the moisture content of the materials in percent wet basis, then the specific heat can be expressed as"

The above relationship exists above 8% moisture content of the grain only.

The specific heat of bone dry grain varies from 0.35-0.45 kcal/kg°C

Prediction of Specific Heat:

For food materials such as eggs, meat, fruit and vegetables, [Siebel 1892]

$$C_p = 0.837 + 3.349 X \text{ (for values freezing)}$$

$$C_p = 0.837 + 1.256 X \text{ (for values freezing)}$$

Where, X is the mass fraction of moisture content.

Heldman [1975] proposed the following equation to estimate the specific heat of foodstuffs using the mass fraction of its constituents (water, fat, protein, carbohydrate and ash):

$$C_p = 4.180 X_{\text{water}} + 1.547 X_{\text{protein}} + 1.672 X_{\text{fat}} + 1.42 X_{\text{CHO}} + 0.836 X_{\text{ash}}$$

Measurement of specific heat:

Calorimeter Method:

The specific heat of the agricultural products can be determined by calorimeter method.

Kazarian used the method of mixture which involves the heating of grain to a constant temperature and then dropping it into water in the calorimeter cup and by using the method of mixture, the specific heat of grain is calculated.

The calorimeter along with stirrer is taken and is weighed with a suitable quantity of water. The temperature of water is recorded. The specimen whose specific heat is to be determined is weighed and is heated in a steam heater. The temperature of the sample is noted. The sample weighed and is heated in a steam heater. The temperature of the sample is noted. The sample is dropped quickly into the calorimeter and drop in the temperature of the mixture is observed.

The mass of the calorimeter and stirrer = W

Specific heat of material of calorimeter = S'

Weight of the water taken = m

Initial temperature of water and calorimeter = $t_1^\circ\text{C}$

Mass of the sample = M

Steady temperature of sample in heater = $t^\circ\text{C}$

Final temperature of the mixture = $t_2^\circ\text{C}$

The required specific heat of sample = S

$$\text{The specific heat } S = \frac{(W S' + m) (t_2 - t_1)}{M (t - t_2)}$$

Method of Guarded Plate:

In this method, the sample is surrounded by electrically heated thermal guards that are maintained at the same temperature as the sample. The sample is also being heated electrically; thus ideally there is no heat loss. The electric heat supplied to the sample in a given time (t) is set equal to the heat gain by the sample as:

$$Mc_p (T_{es} - T_{is}) = VIt$$

Where,

V=voltage (V)

I=current (A)

m=mass of the sample (kg)

T_{ie} , T_{es} =initial and final temperatures of the sample ($^{\circ}\text{C}$)

Thermal Conductivity

The knowledge of thermal conductivity for biological materials is essential for heat analysis during heat and mass transfer problems. The quantity of heat flow through the grain is totally dependent upon the thermal conductivity of the grain.

The thermal conductivity of material is defined as the quantity of heat flow in a unit time through unit area of the cross section of element of the material of unit thickness for unit change in temperature. The value of thermal conductivity is affected by percent of void spaces, shape, size and arrangement of void space and other factors which restrict the heat flow. Thermal conductivity also depends on the ass density of material. Thermal conductivity of single grain is 0.3 – 0.6 kcal/m.hr. $^{\circ}\text{C}$ whereas thermal conductivity of a heap of grain ranges between 0.1 to 0.15 kcal/m.hr. $^{\circ}\text{C}$. The reason for this is the pore space between the grains. These pore spaces are occupied by air whose thermal conductivity is quite lower 0.02kcal/m.hr. $^{\circ}\text{C}$ as compared to grains. Thermal conductivity can be determined by following equation

$$Q = \frac{K A (T_1 - T_2)}{t}$$

Where, Q=amount of heat transferred and K=thermal conductivity

A=area of material perpendicular to direction of heat flow,

T=thickness of material layer,

T_1 & T_2 are the temperature at surfaces of the materials.

Prediction of Thermal Conductivity:

If m is the moisture content of the grain, then the thermal conductivity of wheat can be expressed as follows

Chapter-7 Aerodynamic properties

7.1 Aerodynamic behaviour of grains and their by products.

When grains, seed, fruit and vegetables are mechanically harvested, undesirable materials such as light grains, weed seeds, chaff, plant leaves and stalks can be removed with moving air. In addition, agricultural materials and food products are routinely conveyed using air and water. For operation such as these, the interaction between solid particles and the moving fluid determines the forces applied to the particles. The interaction is affected by the density, shape and size of the particle and density, viscosity and velocity of the fluid.

Drag Forces:-

- When a particle is immersed in a stagnant fluid, it experiences a buoyant force.
- The buoyant force of air is generally insignificant. However when the fluid is moving, additional forces are exerted as a result of fluid momentum. Therefore, even low density fluids such as air can exert substantial forces on the particle.
- For particles free to move assume any orientation in the flow field, only drag forces are significant. In most application with agricultural materials and food products particles are free to assume any orientation in the field.
- The following air exerts two types of forces. They are:-
 - a. Frictional drag (skin friction)
 - b. Pressure drag

Drag Coefficient:-

Fig: Flow about immersed object

When fluid flow occurs about immersed objects, the action of the forces is shown in the figure. The pressure on the upper side of the objects is less than that of the pressure acting on the lower side. In addition to pressure force (acting normal to the surface of the object), there exists shear stresses (T) acting tangential to the surface in the direction of flow and resulting from frictional effects.

The resultant force F_r may be resolved into components, F_D , the drag and F_L , the lift.

The drag and lift force depends upon

- a. Projected area (A_p)
- b. Fluid density (ρ_f)
- c. Viscosity (η)
- d. Modulus of elasticity (E)
- e. Velocity (V)

i.e.

$$F_D = f_1 (A_p, \rho_f, \eta, E, V)$$

$$F_L = f_2 (A_p, \rho_f, \eta, E, V)$$

From dimensional analysis,

Where C_D and C_L are the drag coefficient and lift coefficient of the object respectively.

In most agricultural Engineering application, The moving object is usually free to assume its own orientation.

Hence,

The net resistance force F_r can be given in term of an overall drag coefficient 'C' as follows:

$$F_r = \frac{1}{2} C A_p P_f V^2$$

Further, the resultant force is dissolved into two components:

- Frictional drag (skin friction)
- Pressure drag

Frictional drag:

- It is called by friction between the surface of the kernel and the moving air. It is due to the tangential forces on the body.
- It is also called skin friction.

Frictional drag coefficient is given as:-

- For flat plate with a laminar boundary layer:-

$$C_f = \frac{1.328}{(NR)^{0.5}}$$

- For flat plate with a turbulent boundary layer:-

$$C_f = \frac{0.455}{(\log NR)^{2.58}}$$

- For transition (given by Prandtl 1932)

$$C_f = \frac{0.455}{(\log NR)^{2.58}} - \frac{1700}{NR}$$

Where, N_R = Reynold's number

$$N_R = \frac{V d P_f}{\eta}$$

Where,

V = Velocity

d = effective dimension of the object

η = absolute viscosity of fluid (lb-sec/ft²)

Pressure Drag:-

- The force resulting from pressure differences caused by compression of the air on the upstream end of the particle and rapid expansion of the air on the downstream and of the particle is called pressure drag.
- At higher fluid velocities the skin friction becomes less important and the pressure drag is dominant. Furthermore for relatively dense, spherical or rounded objects such as grains, seeds and particulate materials, there is little surface area over which fluid friction acts and frictional drag is relatively small. In case of plant leaves or husks and chaff, frictional forces may be important.
- When viscous forces predominate i.e. when $N_R < 1.0$, creeping flow, also called Stokes flow occurs. In this type of flow, the streamlines do not separate from the object on the downstream side.
- For creeping flow, Stokes law applies. In the case of a sphere with diameter d_p , the drag force F_D is almost entirely called by skin friction and is given by:

$$F_D = 3\pi \eta v d_p$$

- The profile drag coefficient is found to be,

$$C_D = \frac{24}{N_R}$$

Terminal Velocity:-

- If an object is dropped for a sufficient distance, it will be accelerated by the force of gravity until the gravitation force is balanced by the drag force exerted by the air. It will then fall at a constant velocity called the terminal velocity.

- Grain, seeds, fruits, vegetables, foreign material, plant leaves and stakes and all have their all terminal velocities in air.
- The terminal velocity of different material can be and to determine the air velocity needed to suspend various materials and in some cases can be useful for predicting whether two types of materials can be separated by an air stream.

Expression for Terminal Velocity of material:-

Consider a material of mass (m), density (P_p) with projected area (A_p) falling through a fluid having density (P), then the terminal velocity of the material can be calculated by balancing the forces acting on the material.

At steady state condition:-

$$m \frac{dv}{dt} = F_g - F_d - F_b \dots\dots\dots 1$$

We have,

$$F_g = mg$$

$$F_d = \frac{Cv^2 \rho \times A_p}{2}$$

$$\text{ad } F_b = \frac{m \times \rho \times g}{\rho_p}$$

Putting these terms in eqn. 1

$$m \frac{dv}{dt} = mg - \frac{CV^2 \rho A_p}{2} - \frac{m \rho g}{\rho_p}$$

$$\text{or, } m \frac{dv}{dt} = mg \left[1 - \frac{\rho}{\rho_p} \right] - \frac{CV^2 \rho \times A_p}{2}$$

$$\text{or, } \frac{dv}{dt} = g \frac{\rho_p - P}{\rho_p} - \frac{CV^2 \rho \times A_p}{m^2}$$

For terminal velocity, acceleration=0

$$g \left[\frac{\rho_p - P}{\rho_p} \right] = \frac{CV^2 \rho \times A_p}{2m}$$

$$\text{or, } V^2 = \frac{2m \rho (\rho_p - \rho)}{\rho_p \times \rho \times A_p \pi C}$$

$$V_t = \left[\frac{2m (\rho_p - \rho) g}{\rho_p \times \rho \times C \times A_p} \right]$$

Note: The drag coefficient D given by C which is considered to be an overall drag coefficient such that $C = C_f + C_D$. Where flow is laminar, C_f is negligible. For turbulent flow, C_f is usually negligible except for streamlined bodies.

Terminal velocities of spherical bodies:-

For tangential flow,

$$V_t = \frac{g d p^2 (\rho_p - \rho)}{18 \eta} \quad (\eta = \text{fluid viscosity})$$

For turbulent flow,

$$V_t = 1.74 \left[\frac{g d p (\rho_p - \rho)}{\rho f} \right]$$

For an intermediate region

$$V_t = \frac{0.153 g^{0.714} \times d p^{0.142} (\rho_p - \rho f)^{0.714}}{\rho f^{0.286} \times \eta^{0.428}}$$

Table 10.1. Range of terminal velocities of several types of agricultural material.

| Particle Type | Terminal Velocity, V_t (m/s) | Reference |
|--------------------------|--------------------------------|----------------------------|
| Grains and seeds: | | |
| Barley kernels | 7.3 to 9.0 | Garrett and Brooker (1965) |
| Corn kernels | 9.8 to 11.3 | “ |
| Oat kernels | 7.0 to 8.3 | “ |

| | | |
|-------------------------------|--------------|-------------------------------|
| Soybean seeds | 11.2 to 12.0 | “ |
| Wheat kernels | 8.4 to 9.7 | “ |
| Vegetables: | | |
| Peepers (bell) | 14.1 to 19.7 | Marshall, et al. (1990) |
| Peepers (jalepeno) | 14.5 to 16.5 | “ |
| Biomass: | | |
| Corn cobs | 12.0 to 12.3 | Smith and Stroshine (1985) |
| Corn stalks | 6.4 to 7.2 | “ |
| Wheat heads, threshed | 1.6 to 4.5 | Shellard and Macmillan (1978) |
| Wheat heads, unthreshed | 6.5 to 92 | “ |
| Wheat straw (various lengths) | 2.2 to 6.8 | “ |

$$F_{gravity} = \frac{\rho_p g \pi d^3}{6}$$

$$F_{buoyant} = \frac{\rho_r g \pi d^3}{6}$$

The drag force will be dependent on the projected area of the object, S_p , which is $\pi d^2/4$ for a sphere. The drag force is related to the fluid velocity and S_p by the following equation:

$$F_{drag} = C_D S_p \frac{\rho_f v^2}{2} = C_D \frac{\pi d^2}{4} \frac{\rho_f v^2}{2}$$

Where C_D is the drag coefficient. If the particle is suspended in the fluid, i.e., if it has reached its terminal velocity, v_t , then the drag and buoyant forces, which are acting in the direction which the fluid is moving, are balancing the gravitational force on the particle. Equating F_{drag} plus $F_{buoyant}$ to $F_{gravity}$ gives:

$$C_D \frac{\pi d^2}{4} \frac{\rho_f v_t^2}{2} + \frac{\rho_f g \pi d^3}{6} = \frac{\rho_p g \pi d^3}{6}$$

After like terms are cancelled, this equation can be solved for the terminal velocity v_t of a spherical particle

$$v_t = \sqrt{\frac{4d(\rho_s - \rho_f)g}{3\rho_f C_D}} \quad [10.4]$$

The terminal velocity can be calculated providing the value of C_D is known. The drag coefficient is dependent on the Reynolds number of the particle, which can be considered as the ratio of the inertial to the viscous forces acting on the particle:

$$Re_p = \frac{\rho_f v d}{\mu}$$

When the value of Re_p is less than 0.2, the flow is laminar and the drag coefficient can be determined from:

$$C_D = \frac{24}{Re_p}$$

For Reynolds numbers is excess of 200,000, where the flow is turbulent:

$$C_{D=0.44}$$

Finally, for the values of Re_p between 500 and 200,000:

Numericals:

- The setting velocity of starch granules in water at 70°F was fewel to be 0.1 mm/sec. If the granules density were 93.63 lb/ft³, determine the avg diameter of

the granules in 'mm' if these granules were falling in air, what would be their terminal velocity?

(Assume viscosity of water as 0.98×10^{-3} kg/secm)

Hint: we have,

$$V_t = \frac{gdp^2(\rho_p - \rho_f)}{18\eta}$$

$$\text{Or, } dp^2 = \frac{vt \times 18\eta}{g \times (\rho_p - \rho_f)}$$

$$dp = \left[\frac{vt \times 18\eta}{g(\rho_p - \rho_f)} \right] \dots \dots \dots 1$$

a.

Put, $V_t = 0.0189 \text{ nm}$

$$V_t = 0.1 \text{ mm/sec} = 0.1 \times 10^{-3} \text{ m/sec}$$

$$\eta = 0.98 \times 10^{-3} \text{ kg/sec}$$

$$g = 9.81 \text{ m/sec}$$

$$\rho_p = 93.63 \text{ lb/ft}^3 = 93.63 \times 1.602 \times 10^1 = 1500$$

$$P = 997 \text{ kg/m}^3$$

b. Terminal velocity in air

$$V_t = \frac{gdp^2(\rho_p - \rho_f)}{18\eta}$$

$$dp = \text{from eqn } \dots \dots \dots 1$$

$$\eta = 18.5 \times 10^{-6}$$

$$\rho_p = 1500 \text{ kg/m}^3$$

$$P_f = 997 \text{ kg/m}^3$$

$$V_t = 0.015 \text{ m/sec}$$

2. Estimate the terminal velocity for a particle of animal feed having an intermediate diameter of $20 \mu\text{m}$ falling through standard air (moist air having a density of 1.20 kg/m^3). Assume the particle is spherical and that it is a piece of corn endosperm at 15% moisture content. The velocity of standard air is $1.81 \times 10^{-5} \text{ kg/ms}$.

Solution:

The terminal velocity can be estimated from stoke's equation. The density of the endosperm particle can be assumed to be the same as the particle density of shelled corn, which is given in Table B. 3 for corn at 15% moisture as 1.30 gm/cm^3 or 1300 kg/m^3 . The value of Re_p can be calculated in terms of v_t :

Chapter- 8. RHEOLOGY OF LIQUID AND SEMISOLID FOODS Introduction to Rheology:

Rheology is the science that studies the deformation of materials including flow. Rheological data are required in product quality evaluation, engineering calculations and process design. An understanding of flow behaviour is necessary to determine the size of pump and pipe and the energy requirements. The rheological models obtained from the experimental measurements can be useful in design of food engineering processes if used together with momentum, energy and mass balance.

Liquid foods such as milk, honey, fruit juices, beverages and vegetable oils exhibit simple flow properties. Thicker materials such as creamy salad dressings, ketchup behave in a more complicated manner. Semisolid food such as peanut butter and margarine also behave like both solids and liquids. Most of these food materials are transported by pumping at one stage during processing or packaging, and therefore, their flow behaviour properties are important for determining the power requirements for pumping, for the sizing of pipes, and furthermore, how they relate to sensory characteristics such as food texture. The transport of liquid food by pumps is directly related to liquid properties, especially density and viscosity.

The flow behaviour is also important in the design of process and operations. For example, it is important to determine the type of flow whether turbulent or laminar in heat exchangers. An assumption of simple Newtonian flow can result in error in the estimation of holding time and other equipment design. Rheological properties also serve as a means of controlling or monitoring a process. For example, the apparent viscosity of a general food reduces during enzymatic hydrolysis, whereas apparent viscosity increases during protein denaturation.

8.1 Background

Rheology is related to the study of deformation and flow. It plays an important role during the development, manufacture, and processing of foods and food products. Liquid foods such as milk, honey, fruit juices, beverages, and vegetable oils exhibit simple flow properties. Thicker materials such as creamy salad dressings, ketchup, and mayonnaise behave in a more complicated manner. Semisolid foods such as peanut butter and margarine also behave like both solids and liquids. Most of these food materials are transported by pumping at one stage during processing or packaging, and therefore, their flow behavior properties are important for determining the power requirements for pumping, for the sizing of pipes, and furthermore, how they relate to sensory characteristics such as food texture. The transport of liquid food by pumps is directly related to liquid properties, especially density and viscosity.

The flow behavior is also important in the design of processes and operations. For example, it is important to determine the type of flow whether turbulent or laminar in heat exchangers. An assumption of simple Newtonian flow can result in error in the estimation of holding time and other equipment design. Rheological properties also serve as a means of controlling or monitoring a process. For example, the apparent viscosity increases during protein denaturation.

Flow of material:-

8.1.1 Viscosity

Viscosity is a liquid property that describes the magnitude of the resistance due to shear forces within the liquid. When a fluid is confined between two parallel plates of infinite

Figure 3.1 Imaginary representation of a Newtonian fluid flowing between a stationary plate and moving plate (F=force acting on the plate, v=velocity of moving fluid).

Dimensions, the influence of shear force can be visualized as shown in Figure 3.1. In this scenario, the lower plate is held stationary and the force F is applied on the upper plate to produce a velocity V . This results in a velocity profile within the fluid. The velocity near the stationary plate is zero, whereas the liquid near the top plate will be moving at velocity V in m/s.

The shear force F on the plate area A will shear stress:

$$\tau = \frac{F}{A} \left(\frac{N}{m^2} \right)$$

As the distance between the plates is y , the velocity gradient can be described as dv/dy . This gradient is a measure of the rate of strain or shear rate being applied to the fluid.

3.1.2 Newtonian Fluids

For an ideal Newtonian fluid, the shear stress is a linear function of shear rate, and the proportionality constant for the relationship μ is called the dynamic viscosity.

$$\tau = -\mu \frac{dv}{dy}$$

[3.1]

Many food materials such as milk, apple juice, orange juice, wine, and beer exhibit Newtonian behavior. For Newtonian fluids, viscosity can be determined by applying a single shear rate and measuring corresponding shear stress. But to be accurate, it should always be estimated at several shear rates. The unit of viscosity is $N \cdot s/m^2$, which is Pa.s, whereas in the cgs system, it is $dyne \cdot s/cm^2$ which is also called poise.

1 P = 100 centipoise (cP)

1 cP = 10^{-3} Pa.s or 1 mPa.s

Humans can detect viscosity differences as low as 1 cP.

Newton's law of viscosity:-

Consider a fluid between two large parallel plates of area A , separated by a very small distance Y . The system is initially at rest but at time $t=0$, the lower plate is set in motion in the z -direction at a constant velocity v by applying a force ' F ' in the z -direction while the upper plate is kept stationary. At $t=0$, the velocity is zero everywhere except at the lower plate, which has a velocity ' V '. Then, the velocity distribution starts to develop as a function of time. Finally, steady state is achieved and a linear velocity distribution is obtained. The velocity of the fluid is experimentally found to vary linearly from zero at the upper plate to velocity at lower plate. Corresponding to no-slip conditions at each plate.

Experiments show that the force required to maintain the motion of the lower plate per unit area is proportional to the velocity gradient, and the proportionality constant, ' μ ' is the viscosity of the fluid.

$$\begin{aligned} \tau &= \text{shear stress (N/m}^2\text{)} \\ \mu &= \text{viscosity (Pa} \cdot \text{s)} \\ \frac{dv}{dy} &= \text{velocity gradient} \end{aligned}$$

Negative sign is introduced into the equation because the velocity gradient is negative, i.e. velocity decreases in the direction of transfer of momentum.

Newtonian fluids:

Fluids that follow Newton's law of viscosity are called Newtonian fluids. There the shear stress is a linear function of shear rate and the proportionality constant for the relationship μ is called the dynamic viscosity. Gases, oils, water and most liquids that contain more than 90% water such as tea, coffee, beer, carbonated beverages, fruit juices and milk show Newtonian behaviour.

8.1.3 Non-Newtonian Fluid

For most agricultural materials, including food products such as cream, sugar, syrup, honey, and salad dressing, the relationship between shear stress and shear rate is not linear and these fluids are known as non-Newtonian. Some of these materials have a yield stress, Fluids that do not follow Newton's law of viscosity are known as non-Newtonian fluids. Such fluids obey power law model (Ostwald-de-waele equation)

Newton's fluids can be considered as a special case of this model in which $n=1$ and $K=\mu$. The slope of shear stress versus shear rate graph is not constant for non-Newtonian's fluid. For different shear rates, different viscosities are observed. Therefore, apparent viscosity of a consistency term is used for non-Newtonian fluids.

Figure 3.2 Shear stress versus shear rate for Newtonian, pseudoplastic (shear thinning), and dilatants (shear thickening), Bingham plastic, and Casson-type plastic fluids.

Which must be attained before linear flow begins. These are called Bingham plastic-type fluids, examples are tomato ketchup, tomato paste, etc.

- In Non-Newtonian fluids, the ratio of shear stress to shear rate will change with shear rate and this ratio at a given shear rate is called an apparent viscosity.
 - The most common behavior is pseudoplastic or shear thinning, in which the shear stress versus shear rate curve is convex toward the shear axis as shown in Figure 3.2. These types of materials show a decrease in viscosity on shearing and examples include salad dressing, peanut butter, etc. the viscosity of some common foods is illustrated in Table 3.1.
 - For dilatants-fluids or shear thickening, the shear stress versus shear rate curve is concave toward the shear stress axis. These fluids become thicker and viscosity increases on shearing. Some starch suspensions fall into this category.
 - If the fluid has a yield stress and shear stress versus shear rate curve is convex toward the shear axis, then the fluid is called a Casson-type plastic.
- Table 3.1 Viscosity values of some Newtonian food products

| Product | Temperature °C | Viscosity (mPa.s) |
|-------------------------------------|----------------|-------------------|
| Water | 0 | 1.8 |
| Water | 20 | 1.0 |
| Water | 45 | 0.6 |
| Milk, homogenized | 20 | 2.0 |
| Milk, homogenized | 40 | 1.1 |
| Corn syrup (48% solids) | 27 | 5.3 |
| Cream (10% fat) | 40 | 1.5 |
| Honey | 27 | 4.8 |
| Apple juice (brix 20 ⁰) | 27 | 2.1 |
| Corn oil | 25 | 5.7 |
| Peanut oil | 25 | 6.6 |
| Soybean oil | 30 | 4.1 |

8.1.4 Rheological Models

8.1.4.1 Power law Model

Many rheological models are used to describe the properties of the materials during flow and deformation. In most cases, the shear stress (τ) versus shear rate (dv/dy) curves for pseudoplastic and dilatant materials can be described using a simple power law model as shown in Eq (3.2):

$$\tau = m \left(\frac{dv}{dy} \right)^n$$

[3.2]

In eq. (3.2) m is usually called the consistency coefficient with units Pa.s^n and n is called the flow behavior index, which is unitless. Newtonian fluid is a special case of this model, where $n=1$ and m is the dynamic viscosity. If $n<1$, the fluid is pseudoplastic, if $n>1$, it is dilatant.

3.1.4.2 Herschel-Bulkley Model

In the Herschel-Bulkley model (Eq 3.3), the yield stress term (τ_0) has been added to describe plastic and Casson type plastic behavior.

$$\tau = m \left(\frac{dv}{dy} \right)^n + \tau_0$$

[3.3]

Some flow behavior properties of food that follow the Herschel-Bulkley model are shown in Table 3.2.

3.1.4.3 Casson Model

In the Casson model (Eq 3.4) the shear stress versus shear rate curve can be transformed into a straight line by plotting the square root of the shear stress versus square root of the shear rate. Chocolate is a notable example of this type of fluid.

$$\tau^{1/2} = m \left(\frac{dv}{dy} \right)^{1/2} + \tau_0^{1/2}$$

[3.4]

Table 3.2 Values of consistency coefficient (m), flow behavior index (n), and yield stress (τ_0) for selected foods

| Product | Temperature (°C) | Shear rate, 1/s | M (pa.s^n) | n | τ_0 (Pa) |
|------------|------------------|-----------------|-------------------------|------|---------------|
| Ketchup | 25 | 10-560 | 18.7 | 0.27 | 32 |
| Applesauce | 20 | 3.3-530 | 16.7 | 0.30 | 0 |

| | | | | | |
|---|------|----------|-------|------|------|
| Banana puree (17.7 brix) | 23.8 | 28-200 | 6.08 | 0.43 | 0 |
| Mayonnaise | 25 | 30-1,300 | 6.4 | 0.55 | 0 |
| Tomato juice concentrate (25% solid) | 32.2 | 500-800 | 12.9 | 0.41 | 0 |
| Blueberry pie filling | 20 | 3.3-530 | 6.1 | 0.43 | 0 |
| Chocolate, melted | 46 | - | 0.57 | 0.57 | 1.16 |
| Mustard | 25 | 30-1,300 | 19.1 | 0.39 | 0 |
| Peach puree (20% solid) | 26.6 | 80-1,000 | 13.4 | 0.4 | 0 |
| Comminuted batter meat (15% fat) | 15 | 300-500 | 693.3 | 0.16 | 1.53 |
| Orange juice concentrate (42.5 ⁰ brix) | 25 | 0-500 | 4.121 | 0.58 | 0 |

8.1.5 Temperature Dependency of Fluids on Viscosity

The viscosity of fluids decreases with an increase in temperature. For some fruit juices, the temperature effect can be described using an Arrhenius-type relationship as shown in Eq. (3.5):

$$\mu = \mu_0 \exp\left(\frac{E_a}{RT}\right)$$

[3.5]

Where μ is the viscosity, μ_0 the viscosity at reference temperature. E_a the activation energy, T the absolute temperature, and R the gas constant. A plot between $\log \mu$ versus $1/T$, the reciprocal absolute temperature, can be used to determine the values of μ_0 and activation energy E_a .

8.1.6 Time-dependent Viscosity

In some cases, the apparent viscosity of fluid changes with time, as the fluid is continuously sheared. If the apparent viscosity decreases with the time, the fluid is called thixotropic, and if it increases with time, it is called rheopectic as illustrated in Figure 3.3. if the shear stress is measured as a function of shear rate, and if first shear rate is increased and then decreased, hysteresis will occur in the shear stress rate curves.

8.1.6.1 Thixotropic

In the case of thixotropic foods, the materials structure breaks down as shearing action continues. This type of food materials includes gelatin, cream, shortening, and salad dressing, etc.

8.1.6.2 Rheopectic

In the case of rheopectic fluids, the structure builds up as shearing continues. This type of behavior is not common in the food system, but can occur in a highly concentrated starch solution over long periods of time.

Figure 3.3 Behavior of time-dependent fluids (A, apparent viscosity as a function of time; B, shear stress as a function of shear rate).

8.2 Viscosity Measurement

A rheological measurement is taken by imposing a well-defined stress and measuring the resulting strain or shear or vice versa. The most commonly used experimental geometries for achieving steady shear flow are:

- a. Capillary tube viscometer
- b. Rotational viscometer
 - Searle-type
 - Coquette-type

The use of narrow-gap rheometers such as a cone and plate is relatively small shear rates. At high shear rates, and effects arising from the inertia of the sample make measurement invalid. The edge and end effects result mainly from the finite dimensions of the system, the shape of the free surface, related surface tension, and fracture of the samples.

3.2.1 Capillary Viscometer

In a capillary tube viscometer, viscosity measurement is based on the pressure force that is sufficient to overcome the shear force within the liquid and produces liquid flow at given rate. Consider a small capillary viscometer of length L and internal radius r as shown in Figure 3.4 to measure the liquid viscosity. The shear forces are operating on all internal liquid surfaces for the entire length L and distance r from the tube center. Shear stress, τ force F per unit area, can be calculated as

$$\tau = \frac{F}{2\pi L} \quad [3.6]$$

and the pressure drop ΔP across the capillary is given by

$$\Delta P = \frac{F}{\pi r^2} \quad [3.7]$$

Substituting the value F from Eq. (3.7) into Eq. (3.6) gives

$$\tau = \frac{\Delta P(\pi r^2)}{2\pi r L} = \frac{\Delta P r}{2L} \quad [3.8]$$

Figure 3.4 Schematic diagram showing the shear stress τ and the pressure P balance for a section of capillary tube to measure viscosity.

According to Eq. (3.8), shear stress τ will increase from a value of 0 at the center of the tube to $\Delta P r / 2L$ at the tube wall. By substituting the value of shear stress τ in shear stress and shear rate into Newtonian viscosity (Eq. 3.1), we get

$$\frac{\Delta P r}{2L} = -\mu \frac{dv}{dr} \quad [3.9]$$

Rearranging Eq. (3.9) and integrating from the tube wall at radius R , where $v=0$ to any location r within the velocity profile v , yield

Therefore, velocity can be shown as

$$v = -\frac{\Delta P}{4\mu L} (R^2 - r^2) \quad [3.11]$$

The velocity profile of a liquid with viscosity μ can be shown by Eq. (3.11) at location r , when a pressure ΔP is applied across a length of capillary tube L .

By considering a cross-section area of circular shell within the tube as

$$dA = 2\pi r dr \quad [3.12]$$

The volume of the following liquid in the shell can then be calculated by multiplying the cross-section area (Eq. 3.12) with the velocity:

$$dV = (2\pi r dr)(v) \quad [3.13]$$

By integrating Eq. (3.13) from the tube center at $r=0$ to the tube wall $r=R$ and rearranging, we get Eq. (3.14), which is also known as the classical Hagen-Poiseuille equation:

$$\mu = \frac{\pi \Delta P R^4}{8LV} \quad [3.14]$$

Where R = internal radius of the tube and V = volumetric flow rate.

Since the liquid is Newtonian, anyhow rate-pressure combination will give the same viscosity:

$$\Delta P = \frac{\rho V g}{A} = \rho h g = \frac{N}{m^2} = \text{Pa} \quad [3.15]$$

Substituting the value of ΔP in Eq. (3.14) and measuring the time t during the flow of fluid of a constant value V , the viscosity can be determined from the following equation for a liquid of known density ρ as shown:

$$\mu = \left(\frac{\pi \rho g h R^4}{8LV} \right) t \quad [3.16]$$

Kinematic ($\nu = \frac{\mu}{\rho}$) can be calculated easily from capillary tube viscometer such as the

Cannon-Fenske type (Fig. 3.5) by measuring the time t for draining the liquid between two etched marks in capillary tube bulbs. The ratio of the reservoir should be greater than 10 so that the pressure drop due to the flow in the reservoir can be neglected. Thus, all the terms in the parenthesis in Eq. (3.16) are constant for a capillary viscometer and, therefore, kinematic viscosity can be determined as

$$\nu = c \cdot t \quad [3.17]$$

Kinematic viscosity is measured in stokes. 1 stoke=100 cS= cm^2/s = $10^{-4}\text{m}^2/\text{s}$. 1cS= $10^{-2}\text{cm}^2/\text{s}$. kinematic viscosity has the same unit of measure as the diffusion coefficient. Therefore, it is also called momentum diffusivity and is a function of the fluid molecular properties in turbulent flow.

The capillary viscometer constant c can be determined easily by obtaining values needed or by measuring the efflux time of a fluid of known kinematic viscosity. Once the viscometer constant c is known, the kinematic viscosity of test fluid can be estimated easily. Example A capillary tube viscometer is being used to measure the viscosity of honey at 30°C . The tube radius is 2.5 cm and the length 25cm. a pressure of 10 Pa.

Figure 3.5 Typical Canon-Fenske type capillary viscometer.

Gives a flow rate of $1.25 \text{ cm}^3/\text{s}$. determine the viscosity of honey. You are given $R=2.5\text{cm}$ or 0.025m ; $V=1.25\text{cm}^3/\text{s}$ or $1.25 \times 10^{-6}\text{m}^3/\text{s}$, and $\Delta P= 10 \text{ Pa}$.

Solution Substituting the given values in Eq. (3.14) gives viscosity as

$$\mu = \frac{3.1416 \times 10 (0.025)^4}{8 \times 0.25 \times 1.25 \times 10^{-6}} = 4.909 \text{ Pa.s}$$

8.2.2 Rotational Viscometer

The rheological parameters of non-Newtonian test fluid are estimated from the shear stress and shear rate relationship data generated with a co-axial cylinder viscometer, such as Brookfield LV, RV, or DV viscometers or the hake Rotovisco RV series. In such viscometer types, a spindle or sensing element rotates in a test fluid and measures the torque necessary to overcome the viscous resistance. The degree to which the spring is wound is detected by a rotational transducer, which is proportional to the viscosity of the test fluid.

In a coaxial cylinder rotational viscometer, liquid is placed in the space between the inner and outer cylinders. The measurement involves recording of the torque T required to turn the inner and outer cylinder at a given revolution per unit time. As torque $T = F \cdot r$, $F = \tau A$ ($A = 2\pi r L$), where L is the length of the cylinder and r the radial location between the inner and outer cylinder. Therefore,

$$T = 2\pi r^2 L \tau$$

[3.17]

Or shear stress is

$$\tau = \frac{T}{2\pi L r^2}$$

[3.18]

The shear rate $\dot{\gamma}$ for a rotational system is a function of angular velocity ω ($2\pi N$):

$$\dot{\gamma} = r \frac{d\omega}{dr}$$

[3.19]

By substituting the values of shear stress and shear rate from Eqs. (3.18) and (3.19) in Eq. (3.1), we obtain the viscosity relationship

$$\frac{T}{2\pi \mu r^2 L} = r \frac{d\omega}{dr}$$

[3.20]

Further, to determine the angular velocity between the inner and outer cylinder, we can use the integration as

[3.21]

By using the boundary conditions, at the outer cylinder radius R_0 , the angular velocity $\omega=0$, and at inner cylinder r , integration leads to Eq. (3.22) to determine viscosity as shown:

[3.22]

In a single-cylinder viscometer, the outer cylinder radius R_0 approaches infinity and, therefore, the last term in Eq. (3.22) can be omitted. Many single-cylinder rotational viscometers operate assuming that the wall of the vessel containing the fluid has no influence on the shear stress within the liquid. However, this assumption may not always be true for non-Newtonian fluids and, hence, should be carefully evaluated.

3.2.2.1 Co-axial Cylinder Searle-type System

In this type of rotational viscometer, the inner cylinder called a rotor rotates at a defined speed and the outer cylinder called a cup held constant (Fig. 3.6). The rotating inner cylinder forces the liquid in the annular gap to flow, which offers it resistance depending on its viscosity characteristics. A torque-sensing element placed between the drive motor and shaft of the inner cylinder provides a direct measure of the sample viscosity. Most of the rotational

viscometer is based on this working principle. However, these types of viscometer are limited when low viscous samples are to be measured, since the centrifugal force can turn the flow of liquid from a laminar region to turbulent flow, thus affecting the viscosity measurement.

3.2.2.2 Co-axial Cylinder Couette-type System

In this type of rotational viscometer, the outer cylinder rotates at a defined speed and forces the sample in the annular space to flow. The resistance of the liquid against being sheared transmits a velocity-related torque onto the inner cylinder that will be sensed by a torque sensor attached to it. It is measured by estimating just what counteracting torque is required to hold the inner cylinder stand still.

Example A single-cylinder rotational viscometer with a 2cm radius and 5cm length is being used to measure liquid to measure liquid viscosity. At 6, 9, and 12rpm, the torque

Figure 3.6 Schematic illustration of co-axial cylinder rotational viscometer (Searle and Couette types).

readings of 2.3, 3.7 and 5.0 10^{-3} N cm were measured. Compute the viscosity of the liquid. You are given $R=2\text{cm}$ or 0.02m ; $L=5\text{cm}$ or 0.05m ; $N_1=6\text{rpm}$ or 0.1 rps ; $N_2=9\text{rpm}$ or 0.15rps ; $N_3=12\text{rpm}$ or 0.2 rps ; $T_1= 2.3 \times 10^{-3}$ N cm or 2.3×10^{-5} N m; $T_2= 3.7 \times 10^{-3}$ N cm or 5.0×10^{-5} N m.

Solution Substitute the given values for the first set of data in Eq. (3.14):

$$\mu_1 = \frac{2.3 \times 10^{-5}}{8 \times (3.1416)^2 \times 0.1 \times 0.05} = 5.83 \times 10^{-5} \text{ Pa.s}$$

Similarly for the second set of data, $\mu_2=6.25 \times 10^{-5}$ Pa.s and the third set of data, $\mu_3=6.33 \times 10^{-5}$ Pa.s.

$$\text{Average viscosity } (\mu_{\text{avg}}) = 6.14 \times 10^{-5} \text{ Pa.s}$$

3.3 LAB EXERCISE

3.3.1 Objectives

The objective of this lab exercise are to:

- Determine the Newtonian viscosity of a test fluid using a capillary viscometer.
- Determine the flow behavior curves of Newtonian, pseudoplastic, and dilatants types of food materials using co-axial cylinder viscometer.
- Determine the effect of temperature on the apparent viscosity of Newtonian food material.

3.3.2 Materials and Methods

3.3.2.1 Viscosity Measurement of a Newtonian Fluid

- a. A capillary viscometer such as Cannon-Fenske, size 100 (kinematic viscosity range 2 to 10 cS) or 150 (kinematic viscosity range 6 or 30 cS).
- b. Constant-temperature water bath.
- c. Thermometer.
- d. Suction rubber bulb.
- e. Stopwatch.
- f. 100 mL graduated cylinder.

- g. 100 mL volumetric flask.
- h. Pycnometer flask.
- i. Distilled water, acetone, and trichloroethylene.
- j. Viscosity standards: silicone oils, water.
- k. Test fluids: apple juice, milk, water, noncarbonated drinks, etc.

3.3.2.1.1 Procedure

- a. Fill up a 10 mL graduated cylinder with the test fluid.
- b. Attach a suction bulb to arm G of the viscometer (Fig 3.5). Invert the viscometer and dip arm A in the test fluid. Apply suction until the fluid level reaches the etched mark E. Return the viscometer to the upright position.
- c. Place the viscometer in a desired controlled-temperature water bath and allow the temperature to equilibrate. Record the temperature.
- d. Record the efflux time t for the test fluid to drain between the etched marks C and E by pressing the suction bulb.
- e. Repeat the measurement by applying suction arm A to bring the test fluid level above the C mark.
- f. Rinse the viscometer thoroughly, first with distilled water and then acetone. Dry the viscometer completely before each use.
- g. Follow steps 1 to 5 above for each test fluid and viscosity standards.
- h. Clean the viscometer after each standard solution, first with trichloroethylene and then acetone. Aspirate to dryness.
- i. Determine the densities of each test fluid by filling them in tared 25 mL pycnometer flasks and weighing them accurately.
- j. Determine the capillary viscometer constant C using viscosity standard data such as by measuring the efflux time for a fluid of known kinematic viscosity, as follows:

$$C = v_{\text{known}}/t_{\text{known}} \quad [3.23]$$

- k. Estimate the kinematic viscosity of the test fluid using the viscometer constant and efflux time data.
- l. Record the data in Data Sheet 3.1.

3.3.2.2 Viscosity Measurement of non-Newtonian Foods

- a. Brookfield viscometer: model LV, RV, or DV.
- b. Constant-temperature water bath.
- c. Thermometer.
- d. Four beakers, 600 mL capacity.
- e. Suggested test fluids: pseudoplastic type such as banana puree, tomato paste, French dressing, and mayonnaise; dilatant type such as 50-55% cornstarch in water.

3.3.2.2.1 Procedure for Rotational Viscometer

- a. Pour about 500 mL of the test into a 600 mL beaker and place the beaker in a desired temperature-controlled water bath. Record the product temperature.
- b. Press the auto zero button each time the power is turned on.
- c. Carefully attach a suitable spindle to the viscometer shaft by avoiding any side thrust.
- d. Enter the spindle number by pressing the spindle number entry access key.
- e. Level the viscometer by adjusting screws on the mounting stand and the bubble level on the dial casing.
- f. Insert the spindle in the test fluid up to the immersion groove cut in the spindle shaft.
- g. Set the desired spindle speed by rotating the speed control knob.
- h. Calculate the spindle multiplier constant (SMC) and shear rate constant (SRC) from the following equations and by using the viscometer torque constant (TK) data given for each viscometer model:

$$SMC = \frac{\text{Full-scale viscosity} \times rpm}{TK \times 10,000}$$

[3.24]

$$SRC = \frac{\text{Shear rate}}{rpm}$$

[3.25]

- i. Enter the SRC and SMC values.
- j. Run the viscometer spindle in the test fluid and record the shear stress data at various spindle speeds or shear rates.
- k. Set the viscometer readout display to measure viscosity directly and record viscosity data at various shear rates.
- l. Record the data for each product in Data Sheet 3.2.

3.2.2.2 Effect of Temperature on Product Viscosity

In order to determine the effect of temperature on the test product viscosity, obtain shear stress and shear rate data at two more temperatures such as 40°C and 55°C by using rotational viscometer. Follow the same procedure as before to complete the experiment. Obtain experimental data at various shear rates in order to draw the curves for three different temperatures. Record the data in Data Sheet 3.3.

3.3.3 Results and Discussion.

- a. Report the capillary viscometer constant c by using the efflux time of standard solution.
- b. Calculate the kinematic and dynamic viscosity of the Newtonian test fluid by using viscometer constant c and efflux time data.
- c. Plot the shear stress and shear rate curves for Newtonian, pseudoplastic, and dilatants test fluid data obtained with the co-axial cylinder viscometer, that is, the Brookfield DV type. Do these curves indicate the desired characteristic behavior of the test fluids. If not, why did they deviate from their characteristic behavior?
- d. Plot log shear stress versus log shear rate curves for the above test fluids and estimate their power law parameters such as the consistency index m and flow behavior index n from their intercept and slope values. Write the specific power law equation for each fluid.
- e. Determine the viscosity of a Newtonian test fluid at three different temperatures and compute Arrhenius constant A and activation energy E_a by plotting $\log \mu$ versus $1/T$.
- f. Compare the viscosity data, consistency index values m , and flow behavior index value n of the test fluids from the data available in the literature and discuss your results accordingly.

3.4 Suggested Readings and References

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- b. D.R. Heldman and R.P. Singh, 1981. "Rheology of processed foods." In food processing Engineering. Westport, CT: AVI Publishing Co.
- c. J.F. Kokini, 1992. "Rheological properties of foods." In Handbook of Food Engineering (D.R. Heldman and D.B. Lund, eds.) New York: Marcel Dekker.
- d. J.R. Van Wazer, J.W. Lyons, K.Y. Kim and R.E. Colwell, 1963. Viscosity and Flow Measurement, New York: Interscience Publishers.
- e. J.F. Steffe, I.O. Mohamed and E.W. Ford, 1986. "Rheological properties of fluid foods. In Physical and Chemical Properties of Food (M.R. Okos, ed.), St. Joseph, MI: ASAE.

- f. G. Scchramm, 1981. Introduction to Practical Viscometry, Dieselstrasse, Germany: Haake Buchler Instruments Inc.

DATA SHEET 3.1

Date: _____

Capillary Viscometer type: _____

Product specifications: _____

Capillary viscometer data for Newtonian test fluids

| Product | Density (g/mL) | Viscosity(cP) | Efflux Time (s) |
|-----------|----------------|---------------|-----------------|
| Standard | | | 1. |
| | | | 2. |
| | | | 3. |
| Product 1 | | | 1. |
| | | | 2. |
| | | | 3. |
| Product 2 | | | 1. |
| | | | 2. |
| | | | 3. |
| Product 3 | | | 1. |
| | | | 2. |
| | | | 3. |

Figure 2.2 The operating principle of dynamic mechanical analysis.

2.2.2 Dynamic Mechanical Analysis (DMA)

Unlike the TA-XT2, a dynamic oscillatory rheometer is used mainly for small strain nondestructive tests either in oscillation mode, strain sweep, or stress relaxation mode. The sample is first placed onto the platform and the top plate is lowered to contact the sample (Figure 2.2). The bottom of the plate oscillates at a specified frequency and applies the torque to the sample. A transducer measures the torque transmitted through the sample. The results are given in terms of complex modulus (G^*), storage modulus (G'), loss modulus (G''), complex viscosity, and $\tan \delta$.

Test that can be performed on the DMA include the following:

- Cure test. Holding sample at constant temperature and frequency.
- Temperature sweep. Increasing temperature at a fixed frequency.
- Strain sweep. Increasing the strain amplitude at a fixed frequency.
- Frequency sweep. Increasing the frequency of oscillation at a fixed strain.

- e. Stress relaxation. Relaxation of stress at a constant strain.

Figure 2.3 View of an oscillatory rheometer.

One advantage of using the DMA is the ability to control the temperature over a wide range. Dynamic mechanical thermal analysis (DMTA) generally involves varying temperature, strain amplitude, or frequency while the other two variables are held constant. Of course, for foods containing substantial water content the upper temperature limit is somewhat lower than 100°C. This Chapter refers to a Bohlin (Bohlin Rheologi, Cranbury, NJ) VOR-M rheometer (Figure 2.3), but other instruments are also available.

2.3 Background

In order to design and interpret material tests and their results, it is necessary to understand the basic concepts of stress and strain.

2.3.1 Stress

- Force. The TA-XT2 measures the force needed to deform an object and records in grams, kilograms, pounds force (lbf), or Newton (1kgf=9.807 N). The force depends on the nature of the material, but since it also depends on the dimensions of the test sample, it is not a property of the material alone.
- Stress. The force applied to an object is distributed throughout the entire object. If, at any point within the object, we draw a plane at right angles to this internal force, we can define the stress at that point as the magnitude of the force per unit cross-sectional area:

$$\text{Stress} = (\sigma) = \frac{F}{A} = \frac{\text{Applied force}}{\text{Cross-sectional force}} \quad [2.1]$$

Clearly, the same force applied over a smaller cross-sectional area results in increased stress. Therefore, stress is defined as the intensity of force or a normalized force so to speak.

Example If a rectangular bar that is 2cm high, 1 cm thick, and 4cm long is squeezed at the ends by a 4-N force, the stress at any point in the bar is

$$\sigma = \frac{4N}{0.02m \times 0.01m} = 20,000 \frac{N}{m^2} = 20,000 Pa = 20 kPa$$

- Units of stress. Stress is defined as the force per unit area, analogous to pressure. In fact, hydrostatic pressure is simply one form of stress and has the same units as stress.
- Compressive stress. When an object is placed between a pair of opposing forces that are pointing toward each other as shown in Figure 2.4, the effect is to compress the object. The resulting stress is called the compressive stress. You apply a compressive stress when you squeeze a ball of dough between your hands.
- Tensile stress. When an object is held by a pair of opposing forces that are pulling away from each other as shown in Figure 2.5, the effect is to stretch the object. The resulting stress is called the tensile stress. You apply a tensile stress when you stretch a rubber band.

*Figure 2.4 Principle of compressive stress**Figure 2.5 Principle of tensile stress*

- f. Axial stress. In both compressive and tensile stresses, the pair of applied forces exist along a common axis. These two stresses are, therefore, classified as axial stresses.
- g. Normal stress. In computing either compressive or tensile stress on an object, you divide the applied force by the cross-sectional area of the object that is perpendicular to the axis of the force. Since this area is normal to the force, the stress is called the normal stress.
- h. Shear stress. When a pair of forces are parallel but do not occur along a common axis, the effect is to skew the object. For example, if the top of a rectangular object is pulled to right while the bottom is pulled to the left as shown in Figure 2.6, the object will become a parallelogram. This type of stress is called shear stress:

$$\text{Shear stress} = (\tau) = \frac{F}{A}$$

[2.2]

Where τ usually denotes a shear stress.

- i. Tangential stress. In computing shear stress, the magnitude of the forces is divided by the cross-sectional area of the object that is parallel to the forces. Since the forces are tangential, rather than perpendicular to the area, this is called a tangential stress.
- j. Isotropic stress. A stress that comes equally from all directions, as with hydrostatic pressure, is called an isotropic stress. Isotropic stress is illustrated in Figure 2.7. it is identical to the pressure on the surface of the object:

$$\text{Isotropic stress} = (P) = \frac{F}{A} = \text{Hydrostatic pressure}$$

[2.3]

Figure 2.6 Principle of shear stress.

*Figure 2.7 Principle of isotropic stress.***2.3.2 Strain**

- a. Deformation. When an object is stressed, one or more of its dimensions (say, L) usually changes. The magnitude of this dimensional change (ΔL) is referred to as deformation.
- b. Strain. Under the same stress, a long object is expected to change more than a short object. Thus, deformation is a function of both the nature of the material and its dimensions. In order to have a property that is dependent only on the material, we define strain as the magnitude of the change divided by the initial dimension:

$$\text{Strain} = (\epsilon) = \frac{\Delta L}{L_0} = \frac{\text{Change in Length}}{\text{Original Length}}$$

[2.4]

Both compressive and tensile strain are illustrated in Figure 2.8. This is usually referred to as engineering strain. True strain is given by

$$\epsilon = \ln \left(\frac{L}{L_0} \right)$$

[2.5]

Where L= stressed length after elongation or compression.

Figure 2.8 Principle of compressive or tensile strain.

Example A rubber band 3.00 in long is stretched to 4.50 in. The strain on this rubber band is

$$\epsilon = \frac{4.50 - 3.00}{3.00} = \frac{1.50}{3.00} = 0.50 \text{ (engineering strain)}$$

$$\epsilon = \ln \left(\frac{4.5}{3.0} \right) = 0.41 \text{ (true strain)}$$

Thus, the engineering strain is only an approximation of the true strain for large deformation, but it is nonetheless widely used.

- c. Units of strain. Since strain is always the ratio of two lengths, it is always dimensionless.
- d. Axial strain. When an object is subjected to a compressive or tensile strain, it will decrease or increase in length along the axis of the stress. Such a change is called the axial strain.
- e. Lateral (transverse) strain. When an object is stretched, it usually gets thinner. When it is compressed, it usually becomes thicker. Thus, for any axial strain, there is usually a compensating strain at right angles to the force. This is called a lateral or transverse strain. In Figure 2.9, lateral strain is defined as

$$\epsilon_{\text{lateral}} = \frac{\Delta W}{W}$$

[2.6]

- f. Poisson's ratio. The ratio of lateral strain to axial strain measures the extent to which changes in length are accompanied by changes in nonaxial dimensions, that is, the diameter of a cylinder. It commonly varies from 0 (no bulging) to a maximum of 0.5 (a bulge equal to half the compression). Referring to Figure 2.9, we see that Poisson's ratio is computed as

$$\text{Poisson's ratio } (\mu) = \frac{\epsilon_L}{\epsilon_A} = \frac{\Delta D/D}{\Delta L/L} \quad [2.7]$$

Figure 2.9 Principle of axial and lateral strain.

Example A cylinder of cheese 2.00 in long and 1.00 in in diameter is compressed along its axis to a length of 1.90 in. the diameter of the cylinder increases to 1.04 in:

$$\text{Axial strain} = \frac{2.00 - 1.90}{2.00} = 0.10$$

$$\text{Lateral strain} = \frac{1.04 - 1.00}{1.00} = 0.04$$

$$\text{Poisson's ratio} = \frac{\text{Lateral strain}}{\text{Axial strain}} = \frac{0.04}{0.10} = 0.4$$

Poisson's ratio varies from 0 (no lateral contraction) to 0.5 for no volume change during deformation: Values near 0.5 are typical of elastomers (e.g., rubber), whereas values near 0 can be found for flexible foams, and intermediate values are associated with plastics and metals.

- g. Volumetric strain. When an object is stressed in any way, such as under hydrostatic pressure, its volume changes. This called volumetric strain and is computed as the change in volume divided by the initial volume at gauge or absolute pressure:

$$\text{Volumetric strain} = (\epsilon_{vol}) = \frac{\Delta V}{V_0} = \frac{\text{Change in volume}}{\text{Initial volume}}$$

[2.8]

Example A hard roll is found to occupy 4.00 in³. It is then placed in a tank of water and the pressure is raised to 2 atm. Its volume changes to 3.92 in³. The volumetric strain at this pressure is

$$\epsilon_{vol} = \frac{4.00 - 3.92}{4.00} = \frac{0.08}{4.00} = 0.02$$

- h. Shear strain. Shear strain, as shown in Figure 2.10, is a distortion that takes place when the opposing forces are not in line with each other. Thus, the shear strain equals the tangent of the angle of deformation caused by the shear stress:

$$\text{Shear strain} = (\gamma) = \frac{\Delta L}{L} = \tan(\theta)$$

[2.9]

Where γ usually denotes a shear strain.

Figure 2.10 Principle of shear strain.

Example A piece of gelatin 1.5 in thick is held between two horizontal plates. The top plate is moved 0.1 in to the right, skewing the gelatin. The shear strain is

$$\gamma = \frac{0.10}{1.5} = 0.067$$

And has units of radians.

The angle of deformation in this case is $\theta = \tan^{-1}(0.067) = 0.68^\circ$, indicating that for small strains, $\gamma \sim \theta$.

2.3.3 Relating Stress to Strain

- Elastic material. When a stress is applied to an object, it will usually deform. When the stress is removed, it may or may not return to its original dimensions. A material that returns to its original dimensions is said to be ideal elastic.
- Hooke's law. Hooke's law states that the strain exhibited by an object is directly proportional to the applied stress, that is,

$$\sigma = E\varepsilon$$

[2.10]

Where E is the proportionality constant. A material that obeys this law is said to be a "Hookean solid." In fact, most materials are Hookean in the limit of small strain.

- Young's modulus. The constant E in Hooke's law is called Young's modulus:

$$\text{Young's modulus} = (E) = \frac{\sigma}{\varepsilon} = \frac{\text{Stress}}{\text{Strain}}$$

[2.11]

Young's modulus is a measure of a material's stiffness or resistance to deformation. A plot of stress versus strain for a Hookean material is shown in Figure 2.11. As the applied stress is increased the strain increases in direct proportion. Young's modulus is the slope of this line. For Hookean materials, this modulus depends only on the material and not on its dimensions or the magnitude of the applied stress. It is, therefore, a useful measure of a material property. For example, a large stress applied to a breadstick results in only small deformation with a relatively large modulus,

Figure 2.11 Principle of Hooke's law, that is, a linear response between stress and strain.

Whereas an Angel Food cake that exhibits a smaller stress for the same deformation will have a smaller modulus. Of course, this concept of the modulus only applies in the linear region of a stress-strain curve.

- Units of moduli. Since the denominator of a modulus is always dimensionless, the units of any modulus are the same as the units of stress, namely, force per unit area, for example, Pa [=] N/m².
- Bulk modulus. We can similarly define the bulk modulus for a volumetric changes:

$$\text{Bulk modulus} = (K) = \frac{P}{\varepsilon_{vol}} = \frac{\text{Hydrostatic pressure}}{\text{Volumetric strain}}$$

[2.12]

- Shear modulus. The shear modulus is the ratio of shear stress to shear strain:

$$\text{Shear modulus} = (G) = \frac{\tau}{\gamma} = \frac{\text{Shear stress}}{\text{Shear strain}}$$

[2.13]

8.4 Viscoelastic Properties

Some semisolid foods such as dough, gels, or cheese have both viscouslike and solidlike behavior. These materials are generally known as viscoelastic materials. In a dynamic mechanical test, a specimen is deformed by a strain that varies sinusoidally with time, resulting in a sinusoidally varying stress as shown in Figure 2.12. dynamic testing allows for separation of stresses due to sinusoidally varying strain into its viscous and elastic components. The following analysis is based on Rosen (1993).

- a. Sinusoidal strain. Sinusoidal strain is defined as

$$\gamma = \gamma^1 \sin \omega t$$

[2.14]

Where γ^1 =peak strain of a sinusoidally varying strain, ω = angular frequency (radian/s), t = time(s).

Figure 2.12 Schematic view of sinusoidally varying strain in a typical dynamic

test.

- b. In-phase stress. This component of the total stress (τ^*) is in phase with the strain and defines the storage modulus G' :

$$\tau' = G' \gamma'$$

[2.15]

Where τ' =in-phase stress and G' = storage modulus.

- c. Out-of-phase stress. This component of the total stress (τ^*) is out of phase with the strain and defines the loss modulus G'' :

$$\tau'' = G'' \gamma''$$

[2.16]

Where τ'' = out-of-phase stress and G'' =loss modulus. Note that the phase angle (δ) will be zero for an ideal elastic material and 90° for a purely viscous material, whereas for a viscoelastic material phase angle varies between 0 and 90° .

- d. Complex modulus. The complex modulus is the vector sum of the in-phase and out of phase moduli as shown by Eq. (2.17):

[2.17]

- e. Loss tangent ($\tan \delta$). This is the ratio of the loss modulus to the storage modulus as shown by Eq. (2.18) and represents the ratio of the stress dissipated as heat to that stress stored elastically.

[2.18]

- f. Work. Work done during the first quarter cycle in a sinusoidally varying strain is given by Eq. [2.19]:

[2.19]

The first term above represents elastic or recoverable work, and the second term work dissipated or “lost” as heat. Work done in the second quarter cycle is the same except the sign of the stored energy term is negative, indicating that elastic energy is returned. However, there is always a dissipative loss. The

total energy loss that is converted into heat within the material for a full cycle is given in Eq. (2.20) (Rosen, 1993):

[2.20]

- g. An example of cyclic deformation, low G'' would be preferred in automobile tires, where low heat buildup is desired. On the other hand, in mixing bread dough, a combination of suitable G' and G'' values is needed to allow for some viscous flow, that is, mixing. Doughs are allowed to “relax” after mixing to dissipate the stored elastic energy of mixing.

2.4 Testing Methods

Thus, the material properties of a solid material are characterized by the above four constants: E , G , μ , and K . These four constants are related by

$$E = 3K(1 - 2\mu) = 2(1 + \mu)G$$

[2.21]

This means that only two properties need to be determined experimentally. For elastomer ($\mu=0.5$), the above equation reduces to the well-known equation:

$$E = 3G$$

[2.22]

The above relationship can be used to convert stress-strain data obtained in shear or tensile mode and vice versa. These type of material constants are increasingly being used to characterize food materials. Some of the testing procedures used to determine them will be the focus of this chapter.

2.4.1 Compression Tests

In simple compression tests, a common objective is to determine the Young's modulus of the material. This is done as follows using cheese as an example:

- a. Turn on the TA-XT2 and computer or another force-measuring instrument.
- b. Enter the texture analyzer program.
- c. Enter the cross-head speed (say, 2mm/s), sample surface area (say, 506 mm²).
Compression time (60 s), compression distance (10 mm).
- d. Cut a cheese sample 20mm high, 25mm in diameter using a cork borer.
- e. Place the sample under the probe and start your test:
 - i. This example refers to the test result shown in Figure 2.13. A cheese sample 20mm high with a 25mm diameter was compressed (50% strain) using a TA-XT2 as illustrated in Figure 2.14.
 - ii. At point B, the probe begins to compress the cheese sample. The force read by the instrument is shown on the Y axis.

Figure 2.13 Schematic view of various stages in a compression test on a cheese sample.

Figure 2.14 Typical force versus distance curve obtained for a cheese sample during a compression/relaxation/decompression sequence using the TA-XT2.

- c. At point D the sample has been compressed 10mm and is then held for 10 s. The cheese partly compressed and remains stationary until point E.
- d. With no further movement of the probe, the force no longer rises. However, between points D and E, the cheese is still experiencing a compressive strain, but the force decreases rather than remaining constant. This gradual reduction in force is called stress relaxation and is typical of viscoelastic materials.
- e. At stage E, the probe begins to rise and the force drops quickly.
- f. At point F, the probe is no longer in contact with the sample.
- g. At point G, the probe pulls away from the cheese and the force becomes 0 again. The peak force at point D was 35 Newtons. The surface area = 0.000506 m^2 . Therefore, stress = $35/0.000506 = 69,170 \text{ Pa}$ or 69.17 kPa . The force at point B is 0N and its stress is 0kPa. Therefore, change in stress $\Delta\sigma = (69.17 - 0) = 69.17 \text{ kPa}$. In addition, the change in strain between points D and B is $\Delta\varepsilon = 0.5 - 0 = 0.5$.

$$\text{Elastic modulus } E = \left(\frac{\Delta\sigma}{\Delta\varepsilon} \right) = 138.34 \text{ kPa}$$

Note that the stress-strain curve is linear (or nearly so) in this region. Between points D and E, the modulus is a function of time unlike an ideal elastic material where E would be constant at constant strain.

2.4.2 Energy Considerations

- a. A typical force versus distance curve for a compression test of some product such as cheese is shown in Figure 2.14. If the horizontal coordinate of this chart is converted to cross-head movement with time, we obtain a plot as shown in Figure 2.15. In Figure 2.14, the area under the curve from B-D represents the integration of force and distance and, hence, the work consumed in compressing the cheese.

Figure 2.15 Typical force versus time curve obtained for a cheese sample during compression testing on a TA-XT2.

- b. A curve representing the loading and unloading of the force versus cross-head movement is shown in Figure 2.16. The work of compression is given by the area BCDEXFB in Figure 2.16.
- c. While the cross-head is stationary (10 s at D), internal rearrangements (at constant strain) at the molecular level within the cheese allow partial relaxation of the force exerted by the cheese against the cross-head and dissipate some of the stored energy. Since there is no deformation or movement during relaxation, none of this energy appears as work and so it must be lost as heat. This is shown as the vertical line (DE) in Figure 2.16.
- d. When the cross-head moves up from E to F as shown earlier in figure 2.13, it is pushed by the cheese as it undergoes partial elastic recovery, so the cheese is doing work on the cross-head. In the process, the remainder of the stored energy is recovered. This energy is represented by the light shaded area EXFE in figure 2.16.
- e. The lost energy is the difference between the energy stored and the energy recovered and is represented by the dark shaded area BCDEFB between the compression and recovery curves. Although we stated above that this loss takes place just between D and E, in reality, it takes place throughout the entire process, including the initial compression.

In an ideal elastic material such as rubber, there would be no viscous dissipation loss and the top portion of the curve in Figure 2.16 (D-E) would be horizontal. In addition, points B and F would exist at the same place. In a purely viscous material such as oil or water, there would be no elastic recovery portion of the curve. Materials that exhibit the curves shown in Figure 2.14, 2.15 and 2.16 are termed viscoelastic since they exhibit both viscous and elastic properties, the relative degree to which one predominates over the other depending on the timeframe of the experiment.

2.4.3 Tensile Test

In a tensile test, material is stretched rather than compressed. Such tests are a useful means of characterizing the material properties of fibrous or elastomeric materials. This type of test stimulates the way you might sometimes pull a bread product, licorice, Mozzarella cheese, or jerk with the teeth rather chewing it.

In this test, the test material is clamped between two jaws and these jaws are moved apart. Alternatively, the one end is fixed and the other end is pulled. The cross-head continues to move throughout the test. A typical curve that might be obtained with a tensile test is shown in Figure 2.17.

- a. A-B represents the Hookean proportional limit.
- b. C is the yield point and represents the yield stress. Although the cross-head continues to move and stretch the material, the stress may decrease as a neck is formed. This part of the curve will vary greatly from material to material. For brittle materials, fracture may occur at C and the force may drop down to 0. For some softer materials, plastic flow may continue for some time (C-D) and this portion of the curve may be quite long.
- c. E is the ultimate strength of the material and it ruptures somewhere beyond point E. several material properties can be determined from this curve:
 - Young's modulus. It measures the resistance of the material being stretched and is represented by the slope between A and B. this is referred to as the tensile

Figure 2.17 Schematic engineering stress-strain curve showing critical points (not all points will be seen with all products).

Modulus. A weak rubber band would have a low modulus, whereas a heavy string would have a high modulus. As with the compression test, this modulus is the ratio of stress to strain:

$$E = \frac{\Delta\sigma}{\Delta\epsilon}$$

[2.23]

- Critical strain. A measure of the amount of deformation before internal yield either by fracture or necking. Elongation is expressed as a percent of the original length:

[2.24]

Where L_0 = the initial length of the material (at A) and L = the length of the material at yield (at c).

- Yield stress. The stress at
- Ultimate strength. Strength at point E.
- Toughness or modulus of toughness. The area under a force-deformation curve (say, up to point C or E) represents the work (N m or J) up to either yield or ultimate strength, respectively. The area under the corresponding stress-strain curve would have units of Pa, that is, a modulus of toughness. This is equivalent to dividing the toughness by the sample volume.

In order to perform a tensile test, the test material must be clamped between jaws. In many cases, the pressure exerted by the jaws weakens the material and causes premature failure. This can be prevented by notching the material to a “dogbone” shape as shown in Figure 2.18. The clamps are applied to the wide end sections and the narrower center section becomes a weak point, which promotes failure away from the jaws.

Example A piece of bread is cut into a dogbone and stretched. The dimensions of the piece are as follows: Width at the center = 1cm (0.01m), thickness at the center = 0.2cm (0.002m). Initially, the clamps separation = 8.6cm (0.086m). Cross-head speed = 0.2mm/min. Determine the modulus $\Delta L=50\text{cm}$ (0.05m).

Solution

$$\Delta\varepsilon = \frac{0.05\text{m}}{0.086\text{m}} = 0.58 \text{ (58\% change in length)}$$

Figure 2.18 A typical notched test material cut into a “dogbone” shape for tensile testing.

The change in force over the measured interval is, say, 2N. Therefore, the change in stress over this interval is:

$$\Delta\sigma = \frac{\Delta F}{\text{cross-sectional area}} = \frac{(2.0\text{N})}{(0.01\text{m})(0.002\text{m})} = 100 \times 10^3 \frac{\text{N}}{\text{m}^2} \text{ (100kPa)}$$

The modulus is, therefore,

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{100 \text{ kPa}}{0.58} = 172.4 \text{ kPa (referred to as the initial cross-sectional area)}$$

2.4.4 Flex Test

In a flex test, or 3-point bending test as it is sometimes called, a rectangular wafer of material such as a cracker is suspended across two parallel cylindrical rods as shown in Figure 2.19. A third rod, parallel to the first two, is fastened to the TA-XT2 machine and lowered onto the wafer midway between the supports. Thus, the sample is flexed.

a. Test dimensions

w = width of the wafer in the direction parallel to the support rods

t = thickness of the wafer

L = length of the span between the centers of the parallel rods

D = deflection of the center of the wafer from its original position at any given moment in the test

F = force being exerted to achieve the deflection D

b. Flexural strain. If a wafer is deflected D units from horizontal, the bottom surface is stretched as shown in Figure 2.20. The maximum strain in the outer fibers is computed by

$$\text{Maximum flexural strain} = (\varepsilon_f) = \frac{6Dt}{L^2} \quad [2.25]$$

*Figure 2.19 A typical flex test on an Instron or TA-XT2 machine.**Figure 2.20 A stretch at the bottom of a sample during a flex test.*

Notice that this strain occurs in the horizontal direction, at right angles to the vertical deformation of the chip.

Example If a chip 0.05 in. thick is suspended between rods 3.5 in. apart and is deformed 0.1 in. from the horizontal, the bottom surface of the chip will experience a strain of

$$\text{Flexural strain} = \frac{6(0.1 \text{ in})(0.05 \text{ in})}{(3.5 \text{ in})^2} = 0.00245$$

In other words, the bottom surface at the bend will have increased in length by 0.245%.

- c. Flexural stress. The maximum stress in the outside fibers at the midspan on this bottom surface is computed by

$$\text{Flexural stress} = (\sigma_f) = \frac{3FL}{2wt^2} \quad [2.26]$$

As with the flex strain, this stress is horizontal, at right angles to the applied force.

Example If in the previous example, the chip was 1.5 in wide and the deformation was brought about by a downward force of 0.05 lb, then the stress that is stretching the bottom surface has the following magnitude:

- d. Flexural modulus. It is the ratio of the change in maximum flex stress to the change in maximum flex strain:

$$\text{Flexural modulus} = (E_f) = \frac{\sigma_f}{\varepsilon_f} \quad [2.27]$$

- iii. Right circular cone: like carrot

$$V = \pi \frac{h(r_1^2 + r_1 r_2 + r_2^2)}{3}$$

- Where r_1 and r_2 are minimum and maximum radii and h is the height
- iv. Round – Potato $V = 4\pi r^2/3$
 - v. Cylindrical – cucumber $V = \pi r^2 h$
 - vi. Eliliptical – egg – $V = 4\pi/3 ab^2$

Frictional properties

The frictional properties such as coefficient of friction and angle of repose are important in designing of storage bins, hoopers, chutes, pneumatic conveying system, screw conveyors, forage harvesters; threshers etc.

The rolling resistance or maximum angle of stability in roiling of round shape agricultural materials is useful in designing handling equipment e.g conveying of fruits and vegetables by gravity flow.

In mechanical and pneumatic conveying systems, the material generally moves or slides in direct contact with the trough, casing and other components of the machine. Thus various parameters affect the power requirement to drive the machine. Among these parameters, the frictional losses is one of the factors which must be overcome by providing additional power of the machine. Hence, the knowledge of frictional properties of the agricultural materials is necessary, therefore, some of the important frictional properties of agricultural products have been described here.

Static friction: The friction may be defined as the frictional forces acting between surfaces of contact at rest with respect to each other.

Kinetic friction: it may be defined as the friction forces existing between the surfaces in relative motion.

If F is the force of friction and W is the force normal to the surface of contact, then the coefficient of friction ' f ' is given by the relationship

$$f = \frac{F}{W}$$

The coefficient of friction may also be given as the tangent of the angle of the inclined surface upon which the friction force tangential to the surface and the component of the weight normal to the surfaces are acting.

Rolling resistance: If a round or cylindrical shaped object rolls over a horizontal surface with force, F , and the deformation in surface occurs, there will be a resultant force, R , exerted by the surface on the body as shown in Fig. 1.10. If the moment of forces is taken about point of application of R and the accelerating force is neglected, then

Assuming the deformation of surface as very small, a is approximately equal to r (fig 1.10), then

$$c = \frac{F r}{W} \text{ or } F = \frac{cW}{r} \quad [1.9]$$

Figure 1.10 Force exerted on a wheel in motion.

The terms c and F may be defined as the coefficient of rolling resistance and rolling resistance respectively. It is evident from the equation that for rigid surfaces, small values of c is obtained resulting in smaller rolling resistance. The rolling resistance is directly proportional to the weight of the rolling object and to the coefficient of rolling resistance which is dependent on the rigidity of the supporting surface and indirectly proportional to the effective radius of the rolling object.

Various mechanisms have been designed by making use of difference in rolling resistance of the materials. One such example is the separation of potatoes and stones. The rolling resistance of stones differs from that of potatoes. The equal rolling resistance is observed only in the case of large potatoes and very small stones.

Angle of repose: The angle of repose is the angle between the base and the slope of the cone formed on a free vertical fall of the granular materials to a horizontal plane. The size, shape, moisture content and orientation of the grains affect the angle of repose.

There are two angles of repose

- a. Static angle of repose

It is the angle of friction taken up by granular material to slide upon itself.

- b. Dynamic of repose

It comes in picture when bulk of the grain is in motion like discharge of grain from bins and hoppers. The dynamic angle of repose is more important than static angle.

Measurement of angle of repose

Method I: A wooden frame full of grain sample is mounted on a tilting top drafting table.

The table top is tilted till the grain starts moving over the inclined surface Fig 1.11. The angle of inclination is measured which is the angle of repose of the grain sample.

Figure 1.11: An apparatus for measurement of angle of repose of scale 2 grain container.

Method II: This apparatus consists of a circular platform immersed in a box filled with grain and with a glass window in one side. The platform is supported by three adjustable screw legs, and is surrounded by a metal funnel leading to a discharge hole. The grain is allowed to escape from the box, leaving a free-standing cone of grains on the platform. A travelling microscope is used to measure the heights as shown in Fig 1.12. The angle of repose, ϕ , is obtained from the geometry of the cone as given below.

$$\phi = \tan^{-1} \frac{2(H_a - H_b)}{D_b}$$

[1.9]

When H_a , H_b and D_b are the height of the cone, height of the platform and diameter of the platform respectively. The angle of repose for some of the grains is given in Table 1.4.

Fig. 1.12: Measurement of angle of repose.

1. box 2. window 3. grain 4. circular platform 5. funnel 6. Adjustable leg

*Table 1.4
Angle of repose of some grains*

Effect of moisture content on the angle of repose. It has been found that the angle of repose increases of moisture content of material. This variation of angle of the repose with moisture content occurs because surface layer of moisture surrounding the particle holds the aggregate of grain together by the surface tension.

| Grain | Angle of repose |
|---------|-----------------|
| Wheat | 23-28 |
| Paddy | 30-45 |
| Maize | 30-40 |
| Barley | 28-40 |
| Millets | 20-25 |
| Rye | 23-28 |

An empirical equation has been developed to correlate the angle of repose and moisture content for rice. The equation was tested with the experimental values which gave the correlation coefficient of 97%. The equation is as follows.

$$\tan \phi = an^2 + b \left(\frac{M}{D_{av}} \right) + cs + d$$

[1.10]

Where, ϕ = angle of repose

$$n = \text{shape factor} = \frac{\text{specific surface of solid}}{\text{specific surface of sphere}}$$

M = percent moisture content

D_{av} = average screen particle diameter

s = specific gravity

a, b, c and d = constants

Chapter - 9. Quality Control:

9.1 Introduction:

- Consumers worldwide always demand to have their foods of higher standards or better quality (Shu-Kong Chen, 2002).
- Quality of foods and food products may be defined as “the degree of excellence of the various characteristics that influence consumer acceptance as well as consumer safety” (Sivasankhar, 2005).
- No single program within a food manufacturing company can be as polarizing yet as important as that of quality control.
- The Triple focus is:
 - ✓ To develop a system that protects the brand from enduring regulatory interventions,
 - ✓ Protects the consumer from undue contamination and
 - ✓ Protects the product from undue variation.
- Due to its importance, it is critical that the quality control manager understand what the quality control system is and of what it is composed (Mark Clute, 2009).
- The ISO standard 8402 defined quality as the totality of features and characteristics of a product or service that bear on the its ability to satisfy stated or implied needs.
- Quality control is defined as the operational activities that are used to fulfill requirements for quality.
- As its fundamental core, quality control is defined as a procedures designed to make certain that the end product conforms to a designated set of criteria as set forth by either the company or consumer. The sum of the procedures that the company establishes is considered its quality control system (Mark Clute, 2009).
- In many cases quality means different things to different people. Food quality may be its sensory property (appearance, taste), nutritional value (nutrient content), health benefits (functional ingredient) or safety (physical, chemical, biological).
- There is general consensus that food safety is the very basic right of people and various efforts have been devoted by all sectors to ensure that the goal of safer food for all would be attained (Shu- Kong Chen, 2002).

Objectives of Quality Control:

Quality control is the main aspect of any industries. The satisfaction of consumer determines the future of any product or a company. The objectives of quality control are as follow:

- Reduction cost- To bring about a reduction in per unit cost.
- Utilization of raw materials- To achieve better utilization of raw materials, manpower and machines.
- Maintain quality- To take necessary corrective steps to maintain the quality of products or services.
- Reduce Customer complaints- To achieve greater customer satisfaction by reducing customer complaints.
- Identify faults- To locate and identify the manufacturing processes fault in order to control and minimize scrap and waste.

9.2 Quality Control:

- The quality control is done by the analytical quality control method.
- This method comprises of two parts: one is statistical quality control and other the qualitative or sensory quality control.

- Before any sensory check of the products the statistical quality control methods should followed.
- Statistical Quality Control(SQC) is the application of statistical methodology in quality control. Statistics is concerned with drawing inferences from random samples. Hence statistical quality control includes all those operational techniques in quality control which are concerned with sampling and with evaluating samples in order to take adequate decisions on material, products, manufacturing processes, organization etc.

9.3 Sampling: Purposes and Techniques:

- If the population regarding any survey is almost impossible to reach and expensive to try every single sample, then how large should the subset of samples be to ensure that the results obtained from it would be generalized?
- A single answer to this question is not possible. However, it is clear that the larger the sample size the more closely your sample data will match that from the entire population. When the sample is selected on random basis 3 main types of random sampling techniques can be identified i.e., the simple random sampling, stratified random sampling and systematic sampling.
 - For the simple random sampling method, any sample from the population has an equal chance of being drawn, that is, every sample has the same probability of being selected.
 - If the selected sample is removed factors from the population for subsequent draws, then the method is random sampling without replacement. However, if the selected sample is not removed from the population in such a way that for any new draw the population remains fixed to the original, then the simple random sampling is without replacement.

9.4 Sensory Quality Control:

Sensory evaluation of foods be carried out by human operators or by automated instruments. Sensory evaluation includes quality check on the basis of three factors:

- I. Appearance
- II. Texture
- III. Flavor.

i. Appearance factors:

- The quality of a food item may simply be judged from its appearance when it is placed in front of a consumer. For example, the appearance of foam at the top in a cup of tea or a glass of wine is a quality defect.
- A slightly cloudiness in orange juice is acceptable but not in apple juice, which must be crystal clear.
- Physical factors such as size, shape, freedom from defect/damaged surface, type and transparency and consistency of the product in different evaluation of plant foods including raw materials such as whole fruits and vegetables, as well as in processed plant and animal foods.
- The consistency of viscous or semisolid food products such as tomato sauce, sugar syrup, chocolate syrups, ketchup or honey may be determined by the resistance of the food product to flow using different types of viscometers.
- Likewise the physical properties are also determined by grading and sorting machines and color of the materials can be measured by colorimeters or spectrophotometers.

ii. Textural factors:

- These include various physical factors such as softness, hardness, firmness, juiciness, grittiness or chewiness felt by the consumer when he handles the food with fingers or with the tongue, teeth or palate(mouth feel).
- Any deviation from the expected texture is said to be a quality defect. The texture of foods changes due to aging, improper processing or storage.
- Thus fresh fruits and vegetables become soggy due to over ripening, bread and cakes become stiff.
 - Texture is an important factor in deciding the consumer acceptance of a food. In fact, quality of a food is mainly judged by its freshness/ripeness/ maturity or proper processing.
 - For examples, crispiness of potato chips, firmness and crunchiness of apples.
 - Measuring the resistance offered by the food to an applied force may be related to evaluation of textural quality.

iii. Flavor Factors:

- Evaluation of flavor factor is highly subjective and depends on the discriminating ability of the consumer as flavor includes the sense of smell as well as the sense of taste as experienced by the consumer.
- People differ in their sensitivity to different odors and taste as much as in their preferences for various types of foods.
- Flavor characteristics may be evaluated by instrumental methods as well by panels of judges. The nature and concentration of volatile aroma compound may be determined by gas chromatography.
- Panels of judge consisting of trained individuals are used for evaluating foods, particularly grading of tea, coffee and wines.

9.5 Total Quality Control(TQC) and Total Quality Management(TQM):

- TQM and TQC can be used interchangeably, however generally TQC relates to the specific act of checking that a product is coming off the production line to the expected tolerances and having processes to correct the manufacturing if something is not right.
- It refers to the production checking, correcting and documenting.
- TQM is a broad term, it refers to management methods used to enhance quality and productivity in organizations and industries. It involves the application of quality management principles to all aspects of the business.
- It not only deals with the quality control of the product but also other aspects like the quality of workers, environment, policy and planning of the business etc.
- TQM aims to hold all parties involved in the production process as accountable for the overall quality of the final product or service.

9.8 Sanitation in Food Industries:

- Proper cleaning and sanitation is becoming increasingly important in modern food processing industries as more perishable and hygienically sensitive products come on to the market.
- The microbial load of products must be low to guarantee shelf life and avoid spoilage during distribution.
- Different types of hygiene practice like HACCP and GMPs should be followed for the better quality of products and good health of the customers.

Hazard analysis and Critical Control Points (HACCP):

- This technique is used to analyze potential hazards in an operation, identifying where these may occur and how much these are critical to consumer safety.
- It also establishes control systems that focus on the prevention of such hazards rather relying on end- product testing.
- It is applied in food-chain from primary producer to final consumer. Potentially hazardous foods include sea foods, livestock and poultry meat, dairy products such as cheese and butter, cooked vegetables, preserved fruit products, soft drinks and beverages.
- Potential hazards for such foods arise from pathogenic bacteria, viruses and fungi, toxic chemicals, industrial effluents and physical matters like fibers, particles etc.
- These hazards can occur during all stages of manufacture, from raw materials to the consumption stage.
- Appropriate action is taken to ensure that areas identified as critical control points(CCPs) are kept under control and not allowed to endanger the items produced.

The successful application HACCP requires the full commitment and involvement of the management and the workforce and the multidisciplinary approach such as plant design as per good manufacturing practices(GMP), and trained personnel. The HACCP system consists of the following principles:

- Conducting a hazard analysis with the help of product description and process flow charts.
- Identifying the Critical Control Points(CCPs).
- Determining critical limits for each CCP.
- Establishing a monitoring system for the control of CCP.
- Establishing the corrective action to be taken when monitoring indicates that a particular CCP is not under control.
- Establishing procedures for verification to confirm that the HACCP system is working effectively.
- Documenting all procedures and records appropriate to these principles and their application.
- Subjecting to internal audit, third party audit and certification.
- Training of personnel.

Good Manufacturing Practices (GMPs):

GMPs assure food safety through vigilant measures at the source, product design and process control. It is the preventive approach to the safety of food. The various steps involved in GMPs include:

- Safety of raw materials from contamination by pesticides, toxins, microbes, agro chemicals and animal dung.
- The judicious use of food additives and
- Application of hygiene practices in handling, processing, packaging, labeling, distribution, sale, preparation and use of food products.

9.6 Food Grades and Standards:

To determine the quality of foods, foods are graded and different standards are given to the foods.

ISO 9000 Series:

- ISO 9000 is a family of standards related to quality management systems and designed to help organizations ensure that they meet the needs of customers and other stakeholders.
- The standards are published by ISO, the International Organization for Standardization, and available through National Standard Bodies.
- ISO 9000 deals with the fundamentals of quality management systems, including the eight management principles on which the family of standards is based.
- ISO 9001 deals with the requirements that organizations wishing to meet the standards have to fulfill. ISO 9001:2000 combined the three standards- 9001, 9002 and 9003 into one, called 9001.
 - i. ISO 9001:1987- Model for quality assurance in design, development, production, installation and servicing was for companies and organizations whose activities included the creation of new products.
 - ii. ISO 9002:1987- Model for quality assurance in production, installation, and servicing had basically the same material as ISO 9001 but without covering the creation of new products.
 - iii. ISO 9003:1987- Model for quality assurance in final inspection and test covered only the final inspection of finished product, with no concern for how the product was produced.

Advantages of ISO:

1. Creates a more efficient, effective operation.
2. Increases customers satisfaction .
3. Reduces audits
4. Enhance marketing
5. Improves employee motivation, awareness and morale.
6. Promotes international trade
7. Increases profit
8. Reduce waste and increases productivity.
9. Common tool for standardization.

9.7 Codex Alimentarius Commission (CAC):

- It is an international body under the joint sponsorship of Food and Agriculture Organization (FAO) and World Health Organization (WHO), setting standards containing the requirement for food products aimed at ensuring a sound, wholesome food product, free from adulteration, correctly labeled and presented to the consumer.
- Codex is responsible for the formulation of internationally recognized food standards for all principle foods whether raw, semi processed or processed.
- It also includes provision for ensuring hygienic and nutritional qualities of food, microbiological norms, nature of food additives, identification and elimination of contaminants, method of sampling and analysis and labeling and presentation.

Nepal Quality Certification Mark or Nepal Standard (NS):

- NS is a certification mark employed on the products in Nepal.
- This certification was formed on 2037 BS.
- Nepal Bureau of Standards and Metrology (NBSM) have given Nepal Standard Quality certification mark to about 31 food industries.

FOOD ENGINEERING – Engineering Properties of Foods

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Summary

The engineering properties of foods are important, if not essential, in the process design and manufacture of food products. They can be classified as thermal (specific heat, thermal conductivity, and diffusivity), optical (color, gloss, and translucency), electrical (conductivity and permittivity), mechanical (structural, geometrical, and strength), and food powder (primary and secondary) properties. Most of these properties indicate changes in the chemical composition and structural organization of foods ranging from the molecular to the macroscopic level. Both modern and more conventional measurement methods allow computation of these properties, which can provide information about the macro structural effects of processing conditions in fresh and manufactured foods. Mathematical models have been fitted to data as a function of one or several experimental parameters, such as temperature, water content, porosity, or other food characteristics. Most engineering properties are significantly altered by the structural differences between foods. Several microscopy, scanning, and spectrometric technologies permit close visualization of changes in structure at different levels without intrusion. Microstructure studies have increased understanding of several changes detected in foods resulting from treatment in emerging and conventional unit operations, by relating these changes to engineering property characterization data and models. In the future, structure–property modeling could lead to the synthetic production of natural materials with improved characteristics, provided advances in genetic engineering and biotechnology are incorporated into the food engineering field.

1. Introduction

The word engine, derived from the words engineer and engineering, comes from the Latin word for talent, ingenium. From the onset of the Industrial Revolution to the beginning of the twentieth century, the term was used almost exclusively to describe power machines. Those who designed, built, and operated these machines became known as engineers, and their profession, or expertise, as engineering. In today's technological world, the meaning of the term has expanded to include not only such disciplines or activities as chemical, medical, polymer, or food engineering, but also genetic engineering and social engineering. Although these disciplines have little to do with engines, they heavily rely on the ingenuity from which the term was originally conceived.

It is difficult to define what exactly constitutes an engineering property of a certain food. In general, however, any attribute affecting the processing or handling of a food can be defined as an engineering property. Since many properties are related, there is usually an arbitrary element in their classification. Traditionally, they are divided into the following categories:

- Thermal properties such as specific heat, conductivity, diffusivity, and boiling point rise, freezing point depression.
- Optical properties, primarily color, but also gloss and translucency.
- Electrical properties, primarily conductivity and permittivity.
- Structural and geometrical properties such as density, particle size, shape, porosity, surface roughness, and cellularity.
- Mechanical properties such as textural (including strength, compressibility, and deformability) and rheological properties (such as viscosity).
- Others, including mass transfer related properties (diffusivity, permeability), surface tension, cloud stability, gelling ability, and radiation absorbance.

Nearly all of the above properties are manifestations of a food's chemical composition and structural organization over several orders of length scales—from the molecular to the macroscopic. A change in either composition or structure usually results in a simultaneous change in several properties. Hence it is difficult, if not impossible, to control a single property in isolation. Moreover, properties can be intrinsic, and primarily controlled by the material itself (for example, structural properties like density) and response properties, varying according to the external conditions to which the food is exposed (including colorimetric properties like hue).

Food materials or biological materials in general can display large compositional variations, in homogeneities, and anisotropic structures. Composition can change due to seasonal variations and/or environmental conditions, or in the case of processed foods, properties can be affected by process conditions and material history. For example, North Atlantic fish show dramatic compositional changes in their protein and moisture contents throughout the seasons. Cereals that are puffed up under different moisture and temperature conditions can vary widely in density and cell-size distribution, and exposure of such products to moist atmospheres, sometimes for short periods only, can have dramatic effects on their crispness. Therefore, in many cases the data found in published lists for engineering properties of foods can only be considered as approximate values. Nevertheless, these tabular values are still very useful since a safety factor is added to almost all calculations or designs of food processes and/or operations. An understanding of what affects the engineering properties of foods is essential for their proper interpretation and successful utilization. Therefore, one should always pay attention to the conditions under which the reported properties were determined, especially when response properties are involved.

Early physical property analyses of food products required constant uniform values and were often oversimplified and inaccurate. Nowadays, computational engineering techniques, such as the finite element method, are much more sophisticated and can be used to evaluate non-uniform properties (for example, thermal properties) that change with time, temperature, and location in food products that are heated or cooled. Improvements measuring the compositions of foods are now allowing predictions of engineering properties that are more accurate than previously, since they can be predicted from existing numerical and empirical models of the food's composition, temperature, and porosity. There has always been a tendency to make general correlations in predicting properties of food materials for use in process design equations. A myriad of mathematical functions have already been fitted to experimental data, and models are bringing order to experience with the goal of clarifying which components or interactions are important in a food system.

The Engineering Properties of Foods topic covers different sets of engineering properties that are described in greater detail in specific articles, each with wide applications to food engineering and useful for product characterization and equipment design in food manufacture. Basic definitions, common methods, parameter dependence, modeling, and food engineering applications will dictate the basic pattern followed within most sections. The final section will define how engineering properties and microstructure are related, because foods are complex in both structure and composition, this being the main reason for variability during property determination.

2. Thermal Properties

Most processed and fresh foods receive some type of heating or cooling during handling or manufacturing. Design and operation of processes that involve heat transfer require special attention due to the heat-sensitivity of foods. Thermal properties of foods are related to heat transfer control in specified foods and can be classified as thermodynamic properties (enthalpy and entropy) and heat transport properties (thermal conductivity and thermal diffusivity). Thermo physical properties not only include thermodynamic and heat transport properties, but also other physical properties involved in the transfer of heat, such as freeze and boiling point, mass, density, porosity, and viscosity. These properties play an important role in the design and prediction of heat transfer operations during the handling, processing, canning, storing, and distribution of foods. Heat can be transferred three different ways: by radiation, conduction, or convection.

- Radiation is the transfer of heat by electromagnetic waves (as in a microwave oven).
- Conduction is the transfer of thermal energy due to molecular oscillations (for example, heating of food by direct fire through metal containers).
- Convection is the transfer of heat by bulk movement of molecules in heated fluids such as liquids or gases (for example, air in heated oven or in tank during juice evaporation).

Although all three types of heat transfer can take place simultaneously, generally only one is predominant, depending on the state of the food and the heating system. In many heat transfer processes associated with storage and processing, heat is conducted through the product; heat is transferred by forced convection between the product and a moving fluid (for example, hot air during tray drying), which surrounds or comes in contact with the product.

Basic definitions of thermal properties of foods related to conduction within the product, with reference to properties associated with forced convection through the surface (such as surface heat transfer coefficient), will be mentioned in this section. Measuring techniques will be briefly described, as well as parameters involved during processing applications.

2.1. Definitions:

The thermal properties of foods can characterize heat transfer mechanisms in different unit operations involving heating or cooling. Specific heat, thermal conductivity, thermal diffusivity, boiling point rise, and freezing point elevation are defined as follows:

(a) **Specific heat**, C_p , is the amount of heat needed to raise the temperature of unit mass by unit degree at a given temperature. The SI units for C_p are therefore ($\text{kJ kg}^{-1} \text{K}^{-1}$). Specific heat of solids and liquids depends upon temperature but is generally not sensitive to pressure. It is common to use the constant pressure specific heat, C_p , which thermodynamically represents the change in enthalpy H (kJ Kg^{-1}) for a given change in temperature T when it occurs at constant pressure P :

$$C_p = \left(\frac{H}{T} \right)_P = \left(\frac{\delta H}{\delta T} \right)_P \quad (1)$$

Only with gasses is it necessary to distinguish between C_p and C_v , the specific heat at a constant volume. Assuming there is no phase change, the amount of heat Q that must be added to a unit mass M (kg of mass or specific weight kg/m^3) to raise the temperature from T_2 to T_1 can be calculated using the following equation:

$$Q = MC_p (T_1 - T_2) \quad (2)$$

(b) **Thermal conductivity**, represents the quantity of heat Q that flows per unit time through a food of unit thickness and unit area having unit temperature difference between faces; SI units for κ

$$\kappa \text{ are } [\text{W m}^{-1} \text{K}^{-1}].$$

The rate of heat flow through a material by conduction can be predicted by Fourier's law of heat conduction. A simplified approximation follows:

$$Q = -\kappa A \frac{dT}{dx} \quad (3)$$

where A is the surface area of the food, x is its thickness, T_1 is the temperature at the outer surface where heat is absorbed, and T_2 is the temperature at the inner surface. In other words, κ represents the ability of the food to transmit heat. Unlike specific heat, κ depends on mass density.

(c) **Thermal diffusivity**, α , SI units [m^2/s], defines the rate at which heat diffuses by conduction through a food composite, and is related to κ and C_p through density ρ [kg/m^3] as follows:

$$\alpha = \frac{\kappa}{\rho C_p} \quad (4)$$

Thermal diffusivity determines the speed of heat of three-dimensional propagation or diffusion through the material. It is represented by the rate at which temperature changes in a certain volume of food material, while transient heat is conducted through it in a certain direction in or out of the material (depending if the operation involves heating or cooling).

Eq. (4) shows that α is directly proportional to the thermal conductivity at a given density and specific heat. Physically, it relates the ability of the material to conduct heat to its ability to store heat. In liquid foods, boiling refers to water evaporation, in which water changes from the liquid phase to steam or vapor phase, and water vapor pressure equals the external pressure. Liquid foods contain high molecular weight solids that cause the boiling point to be elevated above that of pure water. The boiling point rise, ΔT_r , is known as the increase in boiling point over that of water in a given liquid food. As the vapor pressure of most aqueous solutions is lower than that of water at the same temperature, the boiling temperature (boiling point) of the solution is higher than that of pure water.

During freezing, water in the food changes to ice while heat is removed by a refrigeration system. During heat removal, the unfrozen water will still contain dissolved food solids. The presence of dissolved solids will depress the initial freezing point a certain amount ΔT_f below the expected solidification temperature for pure water.

Freezing point depression is defined as the temperature reduction ΔT_f . Both the boiling point rise and the freezing point depression of a food are related to its solutes concentration.

Variations in Properties and Methods of Determination:

Precision and accuracy of measurement are important factors in determining thermal properties variations. In commercial heating or cooling applications, computer techniques nowadays provide accuracies of 2–5 percent for most heat-transfer calculations, which provide much lower relative errors than practical boundary condition determinations (for example, air temperature and velocities).

Several methods are known for measuring specific heat and C_p and thermal conductivity κ experimentally. C_p measurement of foods can be determined by methods of mixtures and differential scanning calorimetry (DSC). For methods of mixtures, a calorimeter of known specific heat is used and C_p is determined from a heat exchange balance. In the DSC method, the sample is put in a special cell where the temperature is increased at a constant heating rate. The specific heat of the food is obtained from a single heat thermogram, which relates heat flow as a function of time or temperature. Two experimental methods to determine κ are the Fitch method and the line source method.

In the Fitch method, a solid slab of a certain food receives heat from one layer and conducts it to a copper plug. Conductivity k is obtained from the food's temperature as a function of heat conduction time. The line source method is based on the use of a thermal conductivity probe to measure a temperature–time relation on a thin cylindrical food piece to which constant heat is applied.

Thermal diffusivity α is usually either determined by direct experimental methods or estimated through Eq. (4). Several direct methods for α determination can be based on a one-dimensional heat conduction equation where geometrical boundary conditions are defined. For instance, an apparatus can be used where the sample is located in a special cylinder and immersed in a water bath at constant temperature. Thermocouples located at the center of the sample (axis) and surface of cylinder measure temperature at different heating times. Transient temperature variations are used for the analytical solution. Indirect methods, although they might yield more accurate diffusivity values, require more time and instrumentation for the three-parameter determination (ρ , and $C \kappa p$).

Boiling point elevation ΔT_r at a certain external pressure can be determined from a thermodynamic equation using the latent heat of vaporization and molar fraction of the food. However, the use of these equations requires knowledge of the proportions of specific components of the foods that cause changes in the boiling points. In many cases, estimates for specific components present in higher concentrations can be used.

Sometimes reference liquids under the same vapor pressure conditions can be compared with the food, and charts can be used to determining boiling points at different saturation concentrations. On the other hand, freezing points T_f in foods can be directly determined from the freezing curve (or cryoscope) method without using component concentrations. ΔT_f value can be derived from the temperature plateau after initial temperature depression (or super cooling) on a time-temperature plot. Furthermore, DSC can also be used to determine the onset, peak, and end of freezing.

Foods show extended variability in composition (mainly water, proteins, carbohydrates, fat, ash, and fiber) and structure, and can be turned into even more complex composite materials when heated together, as in the case of many canned and packed foods, pastry, confectionery, and a wide variety of prepared foods. Thermophysical properties depend on the chemical composition of the structure, determined by the physical arrangement and phase distribution of a system. Thus, heat transfer by conduction may take place in several forms depending on the tortuosity of the material, which may vary at different locations. As porous materials

contain a gaseous phase, the value of the thermal conductivity κ , specific heat C_p , and thermal diffusivity α will depend on the internal and external pore space represented by its porosity (see Mechanical properties).

Thermophysical properties are significantly influenced by changes in water content and temperature. During drying, the transfer of heat into food products is accompanied by simultaneous diffusion of water through the product to the surrounding air, provoking differences in thermophysical properties at different regions of the food. Pore size and distribution not only affect heat transfer because of air retention, but also because of the affinity pores have to retain water. The smaller the pore diameter, the greater the surface tension forces, and the more affinity it has for water. Specific heat C_p of foods is drastically influenced by water content. For example, specific heat has been found to vary exponentially with water content in fruit pulps at above ambient temperatures.

Furthermore, nonaqueous components show lower C_p . The specific heats of oils and fats are usually about one-half the specific heat of water, while the specific heat of dry materials in grains and powders is approximately one-third to one-fourth that of water.

As a result of solute water interactions, the C_p of each individual component in a food differs from the C_p of a pure component, and usually changes with the concentration of soluble solids. The same occurs with thermal conductivity κ , where water shows greater relative magnitudes in comparison to other food constituents.

Thus, both κ and C_p increase with increased moisture content. It is common to find a linear relation between thermal conductivity and moisture content at ambient conditions. The effect of temperature on thermophysical properties is not easy to establish because solids (or semisolids), liquid foods, and food emulsions undergo structural changes.

Thermophysical properties of foods change dramatically during the freezing process. Specific heat changes are difficult to predict when free water becomes solid. Bound water or unfrozen water has a different C_p than bulk-frozen water, and ice has a C_p of about one-half that of liquid water. Thus, C_p below freezing is approximately half that of C_p above freezing. Continuous changes in the fraction of frozen water as temperature varies below the freezing point explain this similarity. In fact, specific heat can be utilized to predict the state of water in frozen foods. Thermal conductivity, however, has been found to be high when temperatures allow water to be in liquid or solid state at very low or high temperatures. Yet when temperatures are within the range of -10° to 0°C , shows its lowest values. Freezing point depression has been modeled with the initial freezing point as a function of water content using linear and quadratic equations.

Some thermophysical property models for food systems have been developed as a function of water content or temperature. Additionally, as composition greatly differs between one food and another, other models are linear combinations of water, fat, protein, carbohydrate and/or ash content, and temperature. C_p has been measured at different temperatures in fresh and dried fruits, meats, cereal grains and cereal products, oils and fats, powders, and other dry foods. Although linear correlations of C_p with concentration are known in liquid foods, variations are often neglected for engineering calculations at near room temperature.

General correlations also predict thermal conductivity κ , of food materials for use in process design equations. Linear, quadratic, and multiple correlations of moisture, temperature, and composition can be found for κ in food materials. Some models consider that different components of foods (for example, fibers) are arranged in layers either parallel or perpendicular to the heat flow. In products such as meats, heat is usually transferred parallel to fibers and κ is dependent on the direction of the heat flow. More general in nature are the randomly distributed models, which consider that the food is composed of a continuous phase with a discontinuous phase dispersed within (solid particles being in either regular or irregular array). In porous materials, porosity must be included in the model because air has a κ much lower than that of other food components. Models including density or porosity, and

pressure, have been developed in fruits and vegetables, meat and meat products, dairy products, cereals, and starch.

Several models for predicting α in foods have also appeared in literature; however, most are product specific and a function of water content or temperature. Although the influence of carbohydrates, proteins, fat, and ash on thermal diffusivity has been also investigated, it was found that temperature and water content are the major factors affecting α . Above freezing temperatures; diffusivity varies linearly with temperature or water composition in some foods, while this is not valid at below-freezing temperatures.

2.3. Food Processing Applications

Food thermal properties play an important role in the quantitative analysis of food processing operations. Numerous food processing unit operations are heat or energy sensitive, and the most well known are shown in Table 1. Heat exchanged and resulting temperature–pressure relations must consider the minimization of reactions such as browning, vitamin loss, and oxidation reduction in order to preserve the acceptability and nutritional value of the food. Thermal properties are useful when evaluating capacities of drying systems, or studying the effect of product shrinkage or internal cracking with the aid of mathematical and numerical drying models. Enthalpy and specific heat are required to calculate the heat load in food processing operations.

Specific heat measurement allows evaluation of the structure of foods (for example, fat polymorphism in chocolate). Operation Description Examples Heat transfer medium Processing conditions Pasteurization Removal of pathogenic microorganisms; increasing shelf life Milk, fruit juices, beer, eggs Hot water, steam, electricity/63–85 °C ,15 s–30 min: Sterilization ,Canning, UHT processing, Sterilization of solids and liquid; 6-month shelf life, Sterilization of fluids and aseptic packaging, Meat, fish, soup, vegetables, fruit, milk, cream, custard, desserts, soup, Hot water, steam ,Hot water, steam direct, or indirect, 100–125 °C, 15 min–2 h, 135–150 °C, 1–10 s, Evaporation Removal of water; production of liquid concentrate, Milk, fruit juices, coffee, cheese whey, Steam 40-100 °C, 2 s–2 h, Dehydration Removal of water; production of dried material with low water activity, Milk, potato, vegetables, fruit, meat, fish Hot air, steam, hot water, electricity, 150–250 °C, Cooking and baking, Cooking foods; baking cereal based foods, Catering operations, bread, meat, pipes, cakes Steam, hot air, microwaves ,1 min to several hours/ Frying Immersion in hot oil French fried potatoes, doughnuts, crisps/ Hot oil 100–150 °C, Chilling Reducing temperature to just above ,freezing point, Cold air, indirect refrigeration (ammonia), 10–0 °C/ Freezing Reducing temperature to well below freezing point/ Dairy products, meat, fish, fruit, vegetables, frozen desserts Cryogenic fluids (liquid nitrogen)

Adapted from: Lewis M.J. (1987). Physical Properties of Foods and Food Processing Systems. Chichester, UK: Ellis Horwood.

Table 1. Unit operations involving heat transfer in foods

During processing involving heat, temperature within a food changes continuously, varying not only the food C_p but also the κ . When conduction of heat is involved, thermal conductivity is important to predict or control the heat flux and processing times. In a processing system, it is necessary to predict the time end-point of processing to ensure the efficiency of the equipment. It is also desirable to heat and cool foods as rapidly as possible to improve the economics of the process by increasing the capacity and delivering a better quality product. All processing-time prediction models need the thermal conductivity data of

food where energy transfer is involved. The speed of heat propagation or diffusion through the material is also related to processing times.

Therefore, thermal diffusivity can also participate in processing-time estimation of processes like canning, cooling, freezing, and frying. The equilibrium freezing point can be used for the prediction of thermophysical properties because of the discontinuity exhibited at that point. Accurate freezing point data can also be used to calculate other colligative properties such as effective molecular weight, water activity, bound, free, and frozen water, and enthalpy below freezing point. Knowledge of freezing point is important for analyzing freezing and thawing times of frozen foods. Freezing point data can be used to ascertain chemical purity with regard to whether a sample differs from a natural or desired condition.

The increase in boiling point or boiling point rise (ΔT_r) of liquid foods is a property of interest in evaporators or other types of heat exchanger equipment design and operation. It is worth mentioning the role of the surface heat transfer coefficient, as it is one of the important parameters necessary to design and control food processing equipment where fluids (air, nitrogen, steam, water, or oil) participate. Although it is not a property of a food, it is used to quantify the transfer rate of heat by convection from a liquid or a gas (especially boiling liquids and condensing vapors) to the surface of the foods. It plays an important role when evaluating the effectiveness of heat transfer in processes where hot water or steam is applied through the evaluation of the overall resistances during heat transfer.

3. Optical Properties:

Optical properties are those material properties resulting from physical phenomena occurring when any form of light interacts with the material under consideration. In the case of foods, the main optical property considered by consumers in evaluating quality is color, followed by gloss and translucency or turbidity among other properties. "Color" is the general name applied to all sensations arising from the activity of the retina, and is related to visual appearance of food (shape, size, surface and flesh structure, and defects).

3.1 Definitions

Optical properties are related to consumer judgment on food appearance and produce some kind of visual effect. Among these, color, gloss and translucency can be defined as follows.

- Gloss is the name given to light specularly reflected from a plain smooth surface. It can be defined by a goniophotometric curve, which represents the intensity of light reflected at the surface at different angles of incidence and viewing.
- Color is essentially a beam of light composed of irregularly distributed energy emitted at different wavelengths. Depending on the type of illumination, the same material can show different light qualities and produce different sensations. Foods, along with other materials, have color properties, which depend exclusively on their composition and structure.
- Translucency of foods is defined using an opaque-to-transparent scale. In liquid foods, light passing through changes its path randomly (in other words, is scattered) when interacting with suspended particles. Although light can be transmitted or reflected, the human eye only experiences translucency as a sensory attribute distinct from color. Many food products (such as cloudy fruit and vegetable juices) are neither fully opaque nor fully transparent, but are translucent.

3.2. Methods and Applications

The color perceived when the eye views a food is related to the following three factors: the spectral composition of the light source, the chemical and physical characteristics of the food, and the spectral sensitivity properties of the eye. To evaluate the colorimetric properties of a food, two of these factors must be standardized. Although the human eye can give fairly uniform results, it can be replaced by some instrumental sensor or photocell to provide even

more consistent determinations. Visual colorimeters facilitate visual comparisons and eliminate differences in interpretation between operators.

In practice, visual measurement of color entails comparing the color problem with reference colors available in printed charts under well-defined and favorable conditions for good, reproducible comparisons. Light source, geometry of viewing, and color of background are the most important factors to control. Description of color for purchase specifications of food commodities or packaging materials involves color tolerances, which are defined in one, two, or three dimensions in color space to avoid variability of the human eye. Several systems of color analysis have been created. The most used are the CIE, Munsell, Hunter, and Lovibond systems.

- In the CIE system, spectral curves indicate how the eyes of normal observers respond to various spectral light types in the visible portion of the spectrum. The system is based on the fact that any color can be matched as a suitable mixture of red, green, and blue. These primary combinations are called tristimulus values of color. A certain color can be defined by chromacity coordinates x and y , and by the luminous transmittance or lightness. A chromacity diagram defines different color points that define the standard color of a food. The US Department of Agriculture uses chromacity coordinates to define specifications of color standards for a variety of products.

- In the Munsell system, all colors are described by three attributes: hue (or type of color), lightness relative to the proportion of light emitted), and saturation or purity (associated with clear to dark perception). The hue scale is based on ten hues distributed on a circumference (scaled 1 to 10); the lightness ranges from black to white (0 to 10) and is distributed on a perpendicular line; the purity is of irregular length beginning with 0 for the central gray to the limit of purity obtainable by available pigments in the Munsell book of color. The Hunter system is also a three-dimensional system using parameters L^* , a^* , and b^* in each dimension:

L^* is the lightness (nonlinear),
 a^* is redness or greenness,
 and b^* is yellowness or blueness.

Combination of L^* , a^* , and b^* can be converted to a single color.

- The Lovibond system is a standard method generally used to determine the color of vegetable oils. It involves visual comparisons of light transmitted through a glass couvette using color filters. Vegetable oils are usually expressed in terms of red to yellow. The Lovibond index can also be used to measure color in wines and juices. Computer software packages have been developed that easily convert light transition spectra into CIE, Munsell, Hunter, and Lovibond color indices.

Color can be measured instrumentally with colorimeters, which may be broadly classified as tristimulus colorimeters and spectrophotometers. The difference between spectrophotometers and colorimeters is that the former measures intensity of light through the completely visible spectrum, and colorimeters are designed to measure only some parameters related to sensory colors. Colorimeters are very useful in the quality control of foods, and give results normally correlated with visual measurements. A Munsell colorimeter consists of a circular rotating platform where several colored disks are mixed in different proportions to provide a range of shades to match the color of a certain food product. It is widely used in the food industry for quality control of a number of solid products like tomatoes, fruits, and peanut butter. Tristimulus colorimeters measure both related scales of Munster, Hunter, or CIE systems, which are numerically related. The quality of output for this type of instrument mainly depends on the correct combination of light source, filter, and photocell to obtain a good reproduction of visual response.

Glossmeters measure intensity of light reflected at three angles of incidence and reflection, and normally give results in the form of indices, obtained by comparing the sample reflectance to that of a highly reflective flat glass, used as a calibration standard.

These indices are easy to interpret, in contrast to more difficult goniophotometric curves used in the past for classification. Translucency can be the measurement of the reflection of a thin sample against both a white and black background. From these measurements, the value of reflection from an opaque layer is calculated as a ratio between absorption and scattering to measure scattered light. Additional information on the visual appearance of turbid products such as orange juice can be obtained.

Processing can affect food product color through changes in its physical state and/or pigment content. Color measurement techniques can improve the understanding on processing changes and reaction kinetics in foods. Applications of color measurement for food processing research are many and varied. For instance, color measurement techniques are used for recording desirable color changes in canning salmon with higher oil content, defining translucency of the tissues and green pigment degradation after blanching treatment of green peas, studying browning kinetics, or determining the influence of particle sizes in the final color of powders. Characterization of the color of ingredients can also help to predict the color of the final product—for example, control of raw strawberries for processing into jam. In red wine, the percentage of brown component and the relative loss of anthocyanin can be followed by reflectance measurement during storage.

Glossiness of a product is a property of the smoothness of its surface. When this characteristic is desired, manufacturers try to improve it, as in the case of fruits covered with wax to make them more visually appealing. Translucency is also worth consideration in some liquid foods, such as fruit juices. Its measurement can be determined by considering the contributions of both absorbed and scattered light when traversing these products. For a few clear liquid foods, such as oils and beverages, color is mainly a matter of transmission of light. Other foods are opaque and derive their color mostly from reflection.

Optical properties can be used to perform quality control and continuous inspection during processing operations. Major requirements for a quality control system are ease of calibration and use, stability, precision, speed, cheapness, and industry-wide applicability. A complete color description requires the use of three dimensions, and a control automatic system may be based on this complete specification. Specifications may be set to provide an idea of fruit ripeness, milk or cream discoloration during sterilization, degree of roasting of coffee grains, or browning of apples slices during storage. Continuous color measurements are used in tasks involving color sorting (or “electronic sorting”) by using in-line systems. Color sorting is used for a very wide range of food materials in screening defects. Visible, infrared, and ultraviolet laser beams can provide continuous inspection through scanning of product size, symmetry, damage, irregular shape, fill level, and label placement by adding automatic software in connection with mechanical devices. For example, during conveying of pre-fried potato chips, optical devices detect any with defects (for example, black spots), and automatically deploy an air nozzle to deflect their path from the conveyor belt.

4. Electrical Properties

There are two main electrical properties in food engineering: electrical conductivity and electrical permittivity. Electrical properties are important when processing foods involving electric fields, electric current conduction, or heating through electromagnetic waves. These properties are also useful in the detection of processing conditions or the quality of foods.

4.1. Electrical Conductivity and Permittivity

Electrical conductivity is a measure of how well electric current flows through a food of unit cross-sectional area A , unit length L , and resistance R . It is the inverse value of electrical

resistivity (measure of resistance to electric flow) and is expressed in SI units S/m in the following relation:

$$\sigma = L / (AR) \quad (5)$$

Electrical permittivity is a dielectric property used to explain interactions of foods with electric fields. It determines the interaction of electromagnetic waves with matter and defines the charge density under an electric field. In solids, liquid, and gases the permittivity depends on two values:

- the dielectric constant ϵ' , related to the capacitance of a substance and its ability to store electrical energy; and
- the dielectric loss factor ϵ'' , related to energy losses when the food is subjected to an alternating electrical field (i.e., dielectric relaxation and ionic conduction).

The electrical conductivity of foods has been found to increase with temperature (linearly), and with water and ionic content. Mathematical relationships have been developed to predict the electrical conductivity of food materials: for example, for modeling heating rates through electrical conductivity measurements, or for probability distribution of conductivity through liquid-particle mixtures. Electrical conductivity shows different behaviors during ohmic and conventional heating. At freezing temperatures, electrical conductivity increases with temperature, as ice conducts less well than water. Starch transitions and cell structural changes affect electrical conductivity, and fat content decreases conductivity. As in thermal properties, the porosity of the food plays an important role in the conduction of electrons through the food.

In foods, permittivity can be related to chemical composition, physical structure, frequency, and temperature, with moisture content being the dominant factor. Dielectric properties (ϵ' , ϵ'') are primarily determined by their chemical composition (presence of mobile ions and permanent dipole moments associated with water and other molecules) and, to a much lesser extent, by their physical structure. The influence of water and salt (or ash) content largely depends on the manner in which they are bound or restricted in movement by other food components. Free water and dissociated salts have a high dielectric activity, while bound water-associated salts and colloidal solids have low activity. Power dissipation is directly related to the dielectric loss factor ϵ'' and depends on the specific heat of the food, density of the material, and changes in moisture content (for example, because of vaporization). Permittivity also depends on the frequency of the applied alternating electric field. Frequency contributes to the polarization of molecules such as water. In general, dielectric constant increases with temperature, whereas loss factor may either increase or decrease depending on the operating frequency. Both the dielectric constant ϵ' and loss factor ϵ'' decrease significantly as more water freezes. Reasonable comprehensive tabulations of electrical properties data are available for foods in electronic and printed form.

4.2. Methods and Applications

The conductivity of a material is generally measured by passing a known current at constant voltage through a known volume of the material and by determining resistance. The total conductivity is then calculated simply by taking the inverse of the total resistivity. Basic measurements involve bridge networks (such as the Wheatstone bridge circuit) or a galvanometer. There are other devices that measure electrical conductivity of foods under ohmic or conventional heating conditions, using thermocouples and voltage and current transducers to measure voltage across and current through the samples.

Known methods for measuring dielectric properties are the cavity perturbation, open ended coaxial probe, and transmission line methods. Since modern microwave network analyzers have become available, the methods of obtaining dielectric properties over wide frequency ranges have become more efficient. Computer control of impedance analyzers and network analyzers has facilitated the automatic measurement of dielectric properties over wide

frequency ranges, and special calibration methods have also been developed to eliminate errors caused by unknown reflections in the coaxial-line systems.

Distribution functions can be used in expressing the temperature dependence of dielectric properties. Electrical properties are important in processing foods with pulsed electric fields, ohmic heating, induction heating, radio frequency, and microwave heating. Conductivity plays a fundamental role in ohmic heating, in which electricity is transformed to thermal energy when an alternating current (a.c.) flows through food. As it has potential use in fluid pasteurization, it is important to know the effective conductivity or the overall resistance of liquid-particle mixtures. Furthermore, liquid-particle mixtures can be pasteurized using pulsed electric field technology, where products with low electrical conductivity are better and more energy-efficient to process. Electrical conductivity can be used for acidity studies, therefore, and for monitoring processes where acidity increases, as in fermentations. Crystallization processes (for example, in sugar solutions) can also be monitored with conductivity measurements, as conductivity has been found inversely proportional to viscosity, which in turn follows supersaturation closely. Conductivity measurements have also been used to measure moisture contents in materials, particularly grain products.

The electrical field inside the food is determined by the dielectric properties and the geometry of the load, and by the oven configuration. These properties are also useful in detection processing conditions, or the quality of foods. The major uses for dielectric properties are measuring and heating applications. Permittivity and moisture are closely correlated when the water content is high. Properly designed electrical instruments can be used to determine moisture content or water activity. Knowledge of dielectric properties in partially frozen material is critical in determining the rates and uniformity of heating in microwave thawing. As the ice in the material melts, absorption of energy increases tremendously. Thus, the portions of material that thaw first absorb significantly more energy and heat at increasing rates, which can lead to localized boiling temperatures while other areas are still frozen. Salt affects the situation through freezing point depression, leaving more water unfrozen at a given temperature.

Dielectric properties are also important in the selection of proper packaging materials and cooking utensils, and in the design of microwave and radio frequency heating equipment, because they describe how the material interacts with electromagnetic radiation. Studies of heating uniformity and temperature elevation rate involve dielectric properties. Typical features of power density patterns of a load are large internal hot and cold areas, internal focusing effects, and the edge-heating phenomenon.

For example, when a raw egg is heated it may explode because the power density near its center is much higher than in other parts, causing violent shattering as the interior becomes superheated. The dielectric properties of materials are very important in evaluating the penetration depth of energy (in other words, the distance at which the power drops 37 percent of its value in the material) that can be achieved in a certain food.

5. Mechanical Properties

The mechanical properties mainly result from the structure, physical state, and rheology. They can be subdivided into two groups: structural and geometrical properties, and strength properties. Structural and geometrical properties include mass–volume–area related properties (density, shrinkage, and porosity), and morphological properties (surface area, roundness, and sphericity). Strength properties are related to solid and semi-solid stress and deformation, and intervene in food texture and rheological characterization. These properties are needed for process design, estimating other properties, characterizing foods, and quality determination.

5.1. Structural and Geometrical Properties

5.1.1. Density

This is defined as mass per unit volume (the SI unit of density is kg/m³). Indeed, there are different forms of density such as true, material, particle, apparent, and bulk that can be used, depending on its application in process calculations or product characterization.

The volume measurement method is what determines the difference between them. True and material densities are calculated by excluding volumes occupied by internal and external pores within the food, while particle, apparent, and bulk densities are determined from less accurate measurement methods that include pore volume. A material's volume can be measured by buoyant force, liquid, gas or solid displacement, or gas adsorption, or by estimating the material's geometric dimensions. The buoyant force method for apparent or particle volume determination utilizes sample weight differences in air and water, while the liquid displacement method measures the increase in liquid volume when the material is immersed in a non-wetting fluid such as mercury or toluene. A gas pycnometer is a gas displacement device that uses high pressure air differences in a sample cell connected to a manometer to determine material volume. Apparent or particle density can be determined by coating particles in order to include internal pores in the volume measured. For solid displacement, sand or glass beads can be used instead.

In most engineering designs, solids and liquids are assumed to be incompressible—in other words, density changes moderately with changes in temperature and pressure. In food engineering, the density of solid and liquid foods changes with temperature and pressure and is dependent on temperature and composition. In the case of liquid foods, no generic equations exist to predict the density. In the literature most of the density data is correlated empirically as a function of temperature, water, solids, and fat content. Different types of nonlinear correlation, such as exponential, quadratic, and cubic, are used to relate density and moisture content.

5.1.2. Porosity

Porosity indicates the volume fraction of void space or air space inside a material. Volume determination is relative to the amount of internal (or closed) or external (or open) pores present in the food structure. Therefore, like density, different forms of porosity are also used in food processing studies, namely open pore, closed pore, apparent, bulk, and total porosities. Porosity can be measured by direct and microscopic methods, or can be estimated from density data. Porosity in foods is mainly predicted from empirical correlations, which are valid for individual foods under given processing conditions. Fundamental models exist that are based on the conservation of mass and volume, as well as a number of terms that account for interaction of components and formation or collapse of air or void phase during processing.

5.1.3. Shrinkage

This is the reduction in volume or geometric dimensions during processing. When post processing volume is larger than initial volume, it is termed as expansion. Two types of shrinkage—isotropic and anisotropic—are usually observed in the case of food materials. Isotropic shrinkage is described as the uniform shrinkage of the materials under all geometric dimensions, whereas anisotropic (or non-uniform) shrinkage develops in different geometric dimensions. The former is common in fruits and vegetables while the latter is known in animal tissue, such as in fish. Shrinkage occurs as a result of moisture loss (during drying), ice formation (during freezing), and formation of pores (by drying, puffing, extrusion, and frying). The glass transition theory is one of the concepts proposed to explain the process of shrinkage, collapse, fissuring, and cracking during drying. The methods of freeze-drying and hot-air drying can be compared on the basis of this theory.

Pore disruption and structure hardening, as well as moisture transport mechanisms, counterbalancing internal forces, and environmental pressure, are some of the causes for reduction or collapse in a food structure. Expansion can be caused by gas generation, which is mainly a result of water evaporation and subsequent pore formation within the food structure. More work is needed to develop a fundamental understanding of how pores are formed, or of the collapse mechanism during processing, and their impact on product characterization. Most of the density, shrinkage, and porosity prediction models for liquid and solid foods are empirical in nature. Recent models have been developed to predict porosity during air-drying based on drying temperature, moisture content, initial porosity, and product type.

Two types of surface areas are used in process calculations and product characterization—the outer or boundary surface of a particle or object, and the total surface area of a porous object, or the pore surface area. It is very common to estimate the surface area from its geometric dimensions in the case of a Euclidian geometric object. A Euclidian geometry always has characteristic dimensions and assumes surfaces to be smooth (in other words, with no external pores), such as in spheric, cubic, and ellipsoidal geometries. Many natural patterns are either irregular or fragmented, to such an extreme degree that Euclidian or classical geometry is no help in describing their form. Fractal analysis is used instead to characterize and estimate the surface areas of these shapes. Native and physically or chemically transformed food particles can be characterized by fractals to predict the efficiency of the transformation process and food particle properties, such as adsorption capacity, solubility, puffing ability, chemical reactivity, and emulsifying ability to optimize food ingredient selection for product development and process design. Like fractal analysis, neural networks or artificial intelligence may have potential in modeling surface, shape, and other mechanical properties of foods.

Morphological properties such as roundness and sphericity are also used to characterize a food's shape. Roundness is a measure of the sharpness of the corners of a solid. Sphericity indicates how the shape of an object deviates from a sphere. Sphericity is defined from the volume, surface area, or geometric dimensions of an object. Sphericity and shape factors are also needed in heat and mass transfer calculations.

Size, shape, sphericity, volume, surface area, density, and porosity are important physical characteristics of many food materials in handling and processing operations. Fruits and vegetables are usually graded according to size, shape, and density. Impurities in food materials can be separated by density differences between impurities and foods. Values for surface areas of fruits and vegetables are needed in investigations related to respiration rate in heat transfer calculations for heating or cooling. Density and the shape factor of food materials are also necessary for predicting the freezing and thawing rate.

Volume change and porosity are important parameters in estimating diffusion coefficients for shrinking systems. Porosity and tortuosity are used to calculate effective diffusivity during the mass transfer process.

5.2. Rheology and Texture

Mechanical properties are intertwined with rheology when including strength properties. Mohsenin (1986) defines mechanical properties as “those having to do with the behavior of the material under applied forces.” Rheology has been defined as “a science devoted to the study of deformation and flow,” or as “the study of those materials that govern the relationship between stress and strain.” “Stress” is defined as force components acting on a body per unit cross-sectional area or area of the deformed specimen (SI units in Pa). “Strain” is the change in size or shape (SI units in mm or percentage) of a body in response to the applied force (at a certain time or during continuous change as stress is applied). Rheologically, the behavior of a material is expressed in terms of stress, strain, and time

effects. Therefore, properties that deal with the motion of the material as a result of an applied force can be included as mechanical forces.

Rheological tests express stress–strain relationships and study strain rate dependency. Ideal solids deform in an elastic Hookean manner, while ideal liquids flow in a viscous Newtonian manner; in each case the behavior is independent of the strain rate. Nonetheless, foods are strain-rate dependent. They usually contain some solid and liquid attributes and, rheologically, are termed viscoelastic bodies. In addition, many possess structural elements that “yield” or rupture when forces are applied, thus changing the stress–strain behavior not only with the applied rate of strain, but also with the applied amount of strain. Foods are anisotropic in nature and their mechanical properties may vary in the direction of the stress application.

There are three stresses that are commonly applied to characterize foods mechanically: compressive (directed toward the material), tensile (directed away from the material), and shearing (directed tangentially to the material). Shear stress is the most prevalent with fluids or viscous materials. Since strain is the response of the material to stress, compressive shear and tensile strains can be found. When small deformations are exerted under compression, foods can show a straight line in the stress strain plot, and its slope is called the “Young modulus of elasticity.” Rheologically, a material can deform in three ways: elastic, plastic, or viscous; it can be denoted by a spring friction element and a dashpot arranged in series or parallel, respectively, in rheological models.

Different mechanical situations define how stress can act on a food: static (constant stress or strain), dynamic (varying stress or strain), or impact (stress exerted and removed after a very short period of time). Impact during mechanical handling is the most common cause of mechanical damage to foods. Behavior under static or dynamic stresses governs the extent of potential mechanical injury (for example, during hopper storage or discharge) and can provide valuable information on the design of handling machinery. In cases like these, definitions of creep (when constant stress is applied to a body increasing in strain as a function of time) or stress relaxation (when constant strain is applied to a body) play a role. Solid foods are mechanically characterized by compression tests or impact tests. Universal testing machines give curves of normal force versus deformation, shear forces, creep, and stress relaxation measurements.

The most important mechanical-rheological behavior of fluid or viscous foods is the flow behavior, which can be basically defined as Newtonian, pseudoplastic, and Bingham, indicating viscosity of the material and its dependence on shear rate. In processing, flow properties can influence pumping requirements, flow of fluid through pipes, or even extrusion properties. Flow properties can be determined using any variety of available rheometers or viscometers.

The mechanical properties of foods intersect not only with rheological behavior but also with the texture of foods. In fact, mechanical properties form the basis for food’s sensory properties related to texture (in other words, properties involved with material resistance to mastication). Furthermore, sensory terms that characterize texture of a food can include the rheological principles of stress, strain, and time effects.

Table 2 shows how sensory textural terms are related to typical mechanical characteristics of food. Both the mechanical properties and texture of food relate to the mechanical work that occurs in food processing operations, as they do when they later interact in the consumer’s mouth. For instance, during both mastication and industrial size-reduction processes (for example, slicing, grinding, mashing, pressing), it is desirable to weaken the structure so that it will properly disintegrate when forces are applied.

Primary parameters Secondary

Parameters/ Popular terms/Hardness Soft→Firm→Hard/Cohesiveness
/Fracturability/Chewiness/Gumminess/Crumbly→Crunchy→Brittle/Tender→Chewy→Tough

h/Short→Mealy→Pasty→Gummy/Viscosity Thin→Viscous/Springiness
Plastic→Elastic/Adhesiveness Sticky→Tacky→Goopy/Adapted from Peleg M. and Bagley
E.B., eds. (1983). Physical Properties of Foods.
Westport, CT: AVI Publishing.

Table 2. Mechanical characteristics of food texture

In this way, texture can be defined as those physical characteristics arising from the structural elements of the food that are sensed primarily by the feeling of touch, related to deformation, disintegration, and flow of the food under a force, and measured objectively by functions of mass, time, and length. This indicates that texture studies include structure (molecular, microscopic, and macroscopic) and the manner in which structure reacts to applied forces. It also emphasizes that texture is a multidimensional property comprising a number of sensory characteristics. For instance, the Texture Profile Analysis widely used in industry defines mechanical parameters such as hardness, fracturability, cohesiveness, springiness, chewiness, gumminess, and resilience. Compression tests evaluate texture by compressing the food in one direction and unrestraining it in the other two dimensions to evaluate hardness or strength in solid foods. The puncture test is the oldest one used for food texture determination, and involves the measurement of force necessary to penetrate the test material with a punch.

Sometimes puncture tests imitate the failure involved in mastication and can measure the firmness of a fresh fruit. The introduction of computer readout and analysis of force time plots obtained with Universal Testing Machines allow reading of the maximum forces from the force–time graphs, measuring of slopes, and calculation of areas under the curve, among other features. Highly complex analyses of force–time plots have now become routine.

Structure may refer to the often-complex organization and interactions of food components under the influence of external and internal physical forces. Structure also refers to the size and shape of the components of the food, as well as how they interact to form an organization. Thus, texture properties can predict deformation mechanisms after stress application, effects of heating in baked products, thawing or freezing mechanisms in meats, or changes in the hardness of fleshy fruit tissues during ripening, through structural microscopy studies. Surface structure microscopy can complement the characterization of the strength properties through traditional qualitative methods such as scanning electron microscopy or confocal laser scanning, among other microstructural methods.

6. Properties of Food Powders

Food powders are particle systems that can be used as food products or ingredients. Particle characterization—description of primary properties of food powders in a particulate system—underlies all work in particle technology. Primary particle properties such as particle shape, particle density, porosity, and particle size, control secondary or bulk properties such as mechanical compressibility, cohesion, angle of repose, flowability, segregation, and attrition, among others. Various methods assess both primary and bulk properties of food powders for quality control or process characterization. Powder properties contribute to the understanding of operations like grinding, filtration, sedimentation, centrifugation, spray or freeze-drying, conveying, dosing, hopper storage, mixing, and many others where particles are present as an initial or final product.

6.1. Primary Properties

Several single particle characteristics influence a powder's mechanical properties. These include particle size, particle shape, surface roughness, density, hardness, and adsorption properties. Of these features, particle size is the most important. The “size” of a powder or particulate material is relative. For a particulate material to be considered powder, its approximate median size (50 percent of the material is smaller than the median size and 50

percent is larger) should be less than 1 mm. It is also common practice to talk about “fine” and “coarse” powders; several attempts have been made to standardize particle nomenclature. SI units for particle size are micrometers (or microns) or millimeters depending on the size range. The selection of a relevant characteristic particle size measurement depends on particle shape, which is rarely spherical. Among varied shapes, particles may be compact, plate-like, or needle-like. The term “diameter” refers to the characteristic linear dimension. Particulate food materials are mostly organic in origin and possess diverse individual structures, ranging from extreme degrees of irregularity (ground materials like spices) to an approximate sphericity (starch) or well-defined crystalline shapes (granulated salt). Many definitions have been established to define individual particle diameter.

More important than individual size is the size distribution among the particles. Particle size distribution is directly related to material behavior and/or physical properties of products. Bulk density, compressibility, and flowability of a food powder are highly dependent on particle size and its distribution. In quality control or system property description, measurement of the particle size distribution in food powders becomes paramount. Different types of methods such as sieving, microscope counting techniques, sedimentation, and stream scanning are available for measuring particle size distribution.

Particle density and porosity have been discussed previously, and all of the above mentioned classifications apply to particulate systems as well. Other definitions to take into account are the “loose bulk density” measured after a powder is freely poured into a container, or “compact density” after it is allowed to compress by mechanical pressure, vibration, and impact. In particle technology, density measurement is important in separation processes (in other words, sedimentation and centrifugation) and in pneumatic and hydraulic transport of powders and particulates, or for processing condition definitions. In particular, dehydration or agglomeration processes can significantly affect the extent and nature of pore formation, and hence the true particle density of the material. During mixing, transportation, storing, and packaging particulate material, it is also important to know the primary properties of bulk material.

6.2. Secondary Properties

Bulk density control is a major objective of many food processes, especially when spray drying and grinding. Under low compressive loads (for example, during powder storage on hoppers), bulk density can be related to normal stress. Bulk density and normal stress have been associated in empirical logarithmic or semi-logarithmic relationships, from which a constant slope value is defined as mechanical compressibility. A simultaneous decrease in a powder’s loose bulk density and increase in compressibility indicate greater attractive and cohesive interactions among powders. Mechanical compressibility can also be determined from stress–strain data using Universal Testing Machines or compaction tests, which put the bulk sample in a vertically vibrating system.

Compaction tests simulate density changes during handling and transportation. Binding and frictional interactions among particles when forming a static heap can give an idea of flowability among particles when variations in composition or moisture content occur. The angle that a powder heap forms with the horizontal is denominated angle of repose. More cohesive powders form higher angles while lower angles represent greater flowability to some degree. If determined under pertinent conditions, this magnitude can provide useful information in the design of conveyors or bin discharge. It is also widely used in the food ingredient industry for bulk quality control.

Flow properties determine how a powder will behave in bins, hoppers, feeders, and other handling equipment. They deal with difficulties associated with withdrawing material from storage hoppers without interruption and at the required rate. Flowability is the ease at which a powder flows through a chute or hopper. Flow of powders is approached differently from

known rheological evaluations of flow in fluids. In powders, interactions are studied from the shear stresses needed to make the powder flow under specified normal stress conditions. Shear cells are used according to standard procedures such as Jenike's method. Some powders may not flow because of particle interlocking or friction among particles, which contributes to stabilizing structures in hoppers during storage. Others possess additional inter-particle forces such as electrostatic, van der Waals, or solid-liquid bridging, providing increased compact strength and cohesion among particles and decreasing flowability even more.

Mechanical and chemical interactions among powders depend on the powder's composition, moisture content, surface mechanical characteristics, particle history (for example, from production to storage), particle shape and size, and the manner in which the particles interact geometrically. Food powder particles can also stick together and form stable structures or cakes that can prevent flow due to mechanical forces resulting from variations in temperature and composition (especially moisture and fat content).

Caking is the unwanted, spontaneous agglomeration process that produces mechanically stable lumps in powders, where both size distribution and strength of the agglomerates can vary dramatically. This phenomenon is commonly found in foods with low molecular weight compounds and increased moisture such as fruit powders, sugars, or coffee, and it may occur in different drying processes during powder production.

Many food powders (for example, instant beverages or dry soup mixes) are mixtures of two or more particles of different composition. During conveying, mixing, discharging, charging, bulk storage, and packaging of powders, another undesirable phenomena termed segregation might occur. This is the unwanted separation of fine particles from coarse particles induced by motion during different handling and storage activities, and occurs almost exclusively in free-flowing mixtures. Different indices can give an idea of the level of segregation in a mixture. Another phenomenon that is more product-related is powder attrition, involving the breakdown of particles. In food powders, it is more frequent in agglomerates, mainly because of their multi-particulate structure. Food agglomerates possess brittle characteristics that make the product susceptible to vibration, compressive, shear, or even convective forces applied to the particles during processing. During impact, breakage of brittle particles can occur, as in instant coffee or milk agglomerates. In such cases, density changes can be attributed, at least partly, to progressive changes in particle size distribution and not only to their spatial rearrangement. Indices that characterize attrition effect on agglomerates and brittle powders have also been developed.

7. Role of Food Microstructure in Engineering Properties

Most engineering properties of foods, including the above-described thermal, optical, electrical, and mechanical properties, are significantly altered by structural differences between foods and within them. By researching a food's structure, behavior of properties under different processing conditions can be explained, and different structure–property relationships determined. Food microstructure studies help to explain the external manifestation of the arrangement of structural elements beyond the resolution of the naked eye. The food engineer's task in structural characterization is to find the scaling laws that translate microstructural data into macrostructural behavior in relation to engineering properties.

Food processing may be viewed as a controlled effort to preserve, transform, destroy, or create structure. Microscopy and related techniques make it possible to visualize and identify food components or changes in structure closely without interfering in the food sample's structural arrangements. Formation, rearrangement, or stabilization of new food structures achieved through processing can be better understood from a qualitative microscopic perspective. However, quantitative characterization of interacting forces or energies involved

in the whole structure formation and stabilization through microstructural analysis is still far from being attained.

7.1. Structural Characterization of Foods

Food processing can be defined as the controlled incorporation of materials and energy into a food. From a structural point of view, it combines different restructuring operations mixing molecules and assemblies until a product is created. Changes in engineering properties of foods can be better explained by following changes in structure. Moreover, visual perception of microstructural phenomena can verge upon the understanding of mechanical, electrical, optical, or thermal changes induced by processing of food.

Structure is the spatial arrangement of structural elements (water and oil droplets, gas cells, fat crystals, strands, granules, micelles, and interface) and assemblies (fibers, proteins, cell walls, cells, and tissue), and their interaction governs values for porosity and density. The scale of observation is important in setting up the engineering problem or in finding a solution, since food elements are viewed differently at different scales.

Relationships between engineering properties and structure reflect the interactions occurring at the molecular, ultrastructural, microstructural, and macrostructural level during food processing. Table 3 defines some elements that can be scrutinized at these scale levels. Structure–property relationships describe the way in which physicochemical, functional, technological, and even some nutritional properties of foods are related to their structure. In engineering, microstructure can integrate structural information and data generated by other physicochemical methods to derive structure–property relationships in foods. Within this framework some general uses can be mentioned:

- to obtain physical and morphological information on the system under study at a relevant scale;
- to understand how natural food materials are assembled at different size scales and organization levels, and identify alternatives for disassembling them;
- to determine the type of breakdown occurring in a food and define compression mechanisms of different types of foods; and
- to monitor the controlled destruction of structure during food processing (for example, release of valuable components, development of new structural compounds).

Scale level Intended observations:

Examples/Molecular Molecules and polymers/Interactions between functional groups/Spatial configuration/Different sizes and types of molecules enzymatic cleavage,/hydrogen bonding, and chemical/cross-linking. Functional groups./Ultrastructural Macromolecules/Natural assemblies/Changes in conformation/association and breakdown of macromolecules.

Formation of natural assemblies through nonspecific interactions. Microstructural Colloids/Elements of processed foods Droplets, crystals, segregated phases, air cells, aggregates, fiber, filaments, films./Macrostructural Major structures or phases/Assemblage and bonding./Compressive failure in solids./Particle-particle solid bridges,/vegetable or meat cellular and tissue/layers.

From: Aguilera J.M and Stanley D.W. (1999). Microstructural Principles of Food Processing and Engineering, 2nd edition. MD: Aspen Publishing.

Table 3. Scale levels of scrutiny to relate food structure and engineering properties:

The molecular and supramolecular architecture constituting food structure is continually and increasingly being unraveled by combining powerful analytical techniques such as microscopy, thermal and mechanical analysis, and advanced spectroscopy. A significant number of analytical and microscopy techniques have become available for explaining microstructural phenomena in medicine, biology, and materials science. Technologies already applied include direct light, confocal laser scanning, fluorescence, transmission and scanning

electron, scanning probe, and atomic force microscopy as well as microspectrophotometry, immunolabeling, and x-ray analysis.

Direct microscopic observation of controlled experiments on a stage mounted under the microscope can provide structural information at a resolution about 10³ times smaller than the human eye can perceive. Advanced computer imaging technologies, fluorescent probe developments, and computer designed optics have all been integrally linked with improved analytical light confocal laser scanning microscopes for high-resolution volumetric imaging, used for optically sectioning a sample without intrusion.

Fluorescence microscopy is useful in food science since it can detect substances in low concentrations, and thus allows the visualization of materials not possible by other light microscopy methods. The prevailing need for food scientists to view a wide spectrum of structural organization resulted in the scanning electron microscope (SEM) method, which combines the best features of the light and transmission electron microscope with a magnification of 500 000 times. A wide range of similar microscopes can provide images of surface topography of a specimen at submicron levels, allowing the examination of surfaces of uncoated “wet” specimens at ambient conditions.

Commercial equipment is now available that allows “miniaturization” heating and cooling (freezing) of thin samples or solutions at controlled rates and visualization through charged-coupled device (CCD) cameras linked to a TV monitor and VCR. Scanning probe microscopy and related high-resolution techniques can scan specimen surfaces at the molecular level, by scanning with a sharp probe closely over the sample surface and measuring some function of distance between the material and probe. They can provide estimates of distance and determine spatial distribution of specific structures (for example, particular macromolecules or elements).

Microspectrophotometry is applied to quantitative cytochemistry for determination of nucleic acids, proteins, enzymes, pigments, and hormones. Immunolabeling techniques, the use of probes (antibodies or lectins) that bind to specific sites on individual molecules, is now a standard method in most histology laboratories. An X-ray microanalysis approach routinely provides results with a spatial resolution in cubic μm and complements information obtained from the above-mentioned techniques.

The development of food materials science requires understanding of the physical properties or function of biopolymeric microstructures. Several techniques used in mechanical and polymer science may be coupled with microscopy simultaneously to observe a structure and measure rheological behavior, thermal transitions, and mechanical properties. Micromanipulation techniques borrowed from biology may well be adapted to assess the engineering properties of cells of tissues. Computer-mediated image analysis can help quantify many of the features revealed by microscopic examination of foods: sizes and shapes of cellular components, thickness of cell walls or particle networks in gels, pore size, and size distributions in gels, relative proportions of various phases, and other properties.

The food engineer views microstructure as an opportunity to return to the traditional engineering concept of assembling building blocks by combining heat, mass, and momentum transfer. Food engineers now have the tools to identify picogram quantities of almost any chemical species, to probe the motility of food molecules, and to look inside them with minimal intrusion and in real time for evaluation of almost any food property and the different structural levels present. In the future, structure–property relationships may, with the help of biotechnology and genetic engineering, contribute to synthesizing natural materials with improved characteristics.

7.2. Practical Implications

Foods are dynamic systems where structures vary during storage, distribution, and preparation depending on factors such as composition, acidity, internal pressures, interacting

phases, and environmental conditions such as relative humidity, external pressure, or temperature. Modeling and optimization of engineering properties in current and future food processes will depend not only on better mathematical algorithms or faster and more powerful computers, but also on a clearer comprehension of the underlying phenomena at appropriate relevant scales. During processing, microstructural changes can occur without changing the main composition of a food; they may go unnoticed by the naked eye but be detected using engineering property techniques.

Food microstructure, phase transitions, density, and porosity strongly affect the thermal and transport properties of foods. In mass or heat transfer processes, where diffusion is the main mechanism, the architecture and properties of the intervening elements may explain the magnitude of effective diffusivity. However, other effects such as shrinkage may also contribute to a low instant diffusivity. The study of heat and transport phenomena of foods and biological materials can be advanced through structure visualization in combination with physical measurements. Heat and mass transfer should be understood at the tissue, cellular, and subcellular levels, so that mechanisms prevailing during processing (such as dehydration and extraction) are clearly identified and modeled. For example, confocal laser scanning microscopy revealed, with minimal intrusion and three-dimensional resolution, that cells in the crust of a fried potato strip remain largely intact and oil free, while oil forms an egg-box arrangement surrounding these cells. Thus, the architecture of a processed solid food can be assisted by models that define diffusion coefficients and include individual properties of the phases.

Furthermore, correlations can be made for specific heat and thermal conductivity. In fact, structural conductivity has been modeled in heterogeneous biphasic materials. The microstructural arrangement of food chemical components affects heat conduction during drying operations. Microstructure can be utilized to develop moisture distribution profiles in drying studies. Furthermore, other common phenomena such as radial cracking and formation of channels during drying (for example, through spherical starch granules) can be characterized. Microstructural studies provide complementary information for the optimization of freezing rates. Freezing involves simultaneous immobilization of water as ice and temperature reduction. Along with ice crystallization, extensive microstructural changes occur inside organized tissues. The rate of freezing will determine the sensory quality of foods, as small crystals can be formed at a faster rate. For example, small crystal formation has a tremendous impact on the sensory evaluation of ice cream. The density and shape factor of food materials are also necessary for predicting the freezing and thawing rates.

Porosity, pore distribution, and cellularity can also be assessed with microstructural information in mechanical, thermal, and electrical property studies. Quantifications of pore distributions can be accomplished by image processing/image analysis using either an image from a microscope, or in the case of macroporous foods, an image directly captured by a video camera and macrolense. Volume change and porosity are important parameters in estimating diffusion coefficients of shrinking systems. In cellular materials, compression functions depend on the type of cell wall collapse occurring, which can be brittle or plastic (as in gels). Techniques that quantify the ruggedness of products such as fractal analysis are used to estimate the surface areas of these shapes.

Fractals, in combination with microstructural studies, can predict the efficiency of the transformation process and food particle properties (such as solubility, puffing ability, emulsifying ability) used to optimize food ingredient selection for product development. Mechanical properties in food microstructure are explained by understanding the main mechanisms leading to structure formation, which can be studied using the most appropriate microscopy techniques and supported by other experimental data. Surface structure microscopy can enhance the characterization of the strength properties through traditional qualitative methods such as transmission light microscopy, scanning electron microscopy,

and transmission electron microscopy. Furthermore, the kinetics of structural changes can be inferred from rheological or mechanical responses.

Mathematical models should be derived based on available structural data and previous findings, which allow predictions of properties for any changes in structure (for example, that induced by change in formulation). Through structural microscopy studies, texture properties can predict deformation mechanisms after stress application, effects of heating in baked products, thawing or freezing mechanisms in meats, or changes in the hardness of fleshy fruit tissues during ripening. Controlled destruction of biological materials, such as by pressing or reducing particle size, is needed to release valuable components; microstructural characteristics often dictate the type of breakdown of the material. During roller pressing or milling of fruit pulps or powder cakes, microstructural studies define the rotating directions or speeds of metal rollers in order to obtain the desired product in optimal conditions (for example, faster extraction rates from broken and damaged surface cells). Many foods like meats or vegetables have cellular or fibrous structures that determine mechanical properties. Biochemical microstructural changes in meats (for example, during rigor mortis and cooling) can be monitored by following the stress of a slightly stretched sample. Strain hardening of flesh can also be traced to combined microstructural and molecular changes.

During extrusion, macro- and microstructures are formed by diverse frictional and other mechanisms involving heat release or application. Microscopy, gel permeation, chromatography, and viscosity measurements have demonstrated fragmentation of the starch granule during extrusion as a result of shear at the subcellular level. Distinctive desirable textures controlled by die design and extruder operating conditions can be assured from studies that combine mechanical strength properties and microstructural characterization. Understanding the nonlinear interactions between the levels becomes essential to controlling the texture of food.

In rheology, deviations from ideal Newtonian behavior in complex fluids can be traced back by defining the role of macromolecules or particles and their interactions through structural modeling of flow conditions over time. Viscosity will depend on solid-like networks, shear-induced deformation, and transient superstructures at different shear rates. Microscopic image analysis tools can be adapted to represent different shear and normal stresses to express flow at different points of a fluid. Nondestructive methods such as dynamic oscillatory rheometry or mechanical spectroscopy are particularly suitable for this purpose.

Powder flowability is determined by particle deformability and surface roughness (or friction). Flow properties in powders can also be monitored with microstructural surface characterization techniques. Surface topography is also important in determining friction in sliding conveyors and between particles, or attrition in the breakdown of powders. Attrition mechanisms of food powders have been assessed through the detection of crack propagation paths detected by scanning electron microscopy.

Electrical properties can also be used to evaluate desirable or undesirable characteristics of some foods. Some examples that can be correlated with microstructural modeling are measurement of heat damage to artificially dried shelled corn, testing the degree of injury and death suffered by plant tissues, detecting frost hardness in some food materials, or determining egg quality and freshness of fish. Optical properties are also related to microstructure due to the compositional chromatic elements of foods. Their distribution within a food can be monitored through hierarchical studies at different levels on the structure and location of these components.

Advances in genetic engineering and biotechnology will forge a new path where naturally synthetic components and raw food materials with modified properties will be fabricated at the molecular and microstructural level. The application of "nanotechnology" will allow the manufacture and positioning of specific molecules or functional groups within food microstructures.

Glossary

Boiling point: Temperature at which the pressure exerted by liquid vapor equals the pressure exerted by the surroundings of the liquid.

CIE: Commission Internationale de l'Éclairage.

CLSM: Confocal laser scanning microscopy.

Electron

microscopy: A type of microscopy that, by using an electron beam, can attain larger resolution than that produced by a light source.

Engineering: The application of science and mathematics, in which the properties of matter and the sources of energy in nature are made useful to humans for the design and manufacture of complex products.

Extrusion: The forcing of a material through a die by rotating a screw inside a barrel in order to obtain different shapes such as ribbons or ropes.

Freezing: A food preservation process that immobilizes the water in a food at low temperatures (generally below -18°C), forming ice within an amorphous matrix.

Freezing point: The temperature at which the liquid and solid states of a food are in equilibrium at a given pressure (normally atmospheric).

Microscopy: An investigation technique that produces enlarged images of minute zones in an object.

Microstructure: Study of the arrangements and interactions of elements in a food responsible for its structure, as observed under a microscope.

Porous food: Food containing a significant internal void space.

SEM: Scanning electron microscopy.

Steady state: A term used to describe the relationship between process variables and time. If the variables change over time, the process is known as steady state; otherwise, the process is called non-steady state or transient.

Structureproperty relationships: Relationships between the internal structure, process, and resulting engineering properties of a material.

Thermocouple: A device for measuring temperature, consisting of two adjoining wires composed of different metals or alloys, which respond to heat with electric tension.

TEM: Transmission electron microscopy.

Unit operation: A process step in which a well-defined transformation occurs, such as changes in temperature, location, size, or composition.

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Biographical Sketches

Gustavo V. Barbosa-Cánovas received his B.S. in Mechanical Engineering at the University of Uruguay and his M.S. and Ph.D. in Food Engineering at the University of Massachusetts, Amherst, MA. He then worked as an Assistant Professor at the University of Puerto Rico from 1985–90, during which he was granted two National Science Foundation (NSF) awards for research productivity. Following this he went to Washington State University (WSU), where he is now Professor of Food Engineering and Director of the Center for Nonthermal Processing of Food (CNPf). Dr. Barbosa-Cánovas chaired the Organizing Committee for the 1997 and 1999 Conference of Food Engineering (CoFE). In addition, he is an Editor of the journal Food Science and Technology International published by Sage, the journal Innovative Food Science and Emerging Technologies published by Elsevier Science, and the Food Engineering theme in the Encyclopedia of Life Support Systems (EOLSS) to be published by UNESCO.

Dr. Barbosa-Cánovas is the Editor-in-Chief of the Food Engineering Book Series published by Kluwer Academic and Plenum Publishers (KAPP) as well as of the Food Preservation Technology Book Series published by CRC Press. He has chaired and organized several technical sessions at the American Institute of Chemical Engineers (AIChE) and Institute of Food Technologists (IFT) annual meetings, edited twelve books on Food Engineering topics, and authored, among others, Dehydration of Foods (Chapman & Hall), Nonthermal Preservation of Foods (Marcel Dekker), Food Engineering Laboratory Manual (Technomic), and Engineering Properties of Biological Materials (ASAE). Dr. Barbosa-Cánovas is also a member of the editorial board for four technical journals, including the Journal of Food Engineering, Journal of Food Process Engineering, Journal of Food Science and Technology (LWT), and the International Journal of Physical Properties of Foods. He is International Consultant for the United Nations' Food Agriculture Organization (FAO), Associate Researcher for the United Nations' PEDECIBA (a special program to develop basic sciences), and a consultant for several major food companies in the United States.

Pablo Juliano received a B.S. in Chemistry from the University of Uruguay in 1999. In 2000, he was awarded a scholarship from the Organization of American States to pursue graduate studies at Washington State University toward an M.S. in Food Engineering, where he

received his Ph.D. in 2006. He also worked in quality assurance at Nestle (Uruguay) between 1996 and 2000, where he applied his ISO 9000 Quality Specialist Degree. Dr. Juliano specialized in food powder technology and high pressure processing of food.

Micha Peleg is Professor of Food Engineering at the University of Massachusetts, Amherst, MA in the Department of Food Science (since 1990). He first obtained his B.Sc. (Chemical Engineering) at Technion, Israel Institute of Technology in 1963, his M.Sc. (Food Engineering and Biotechnology) at Technion in 1967, and his D.Sc. (Food Engineering and Biotechnology) at Technion in 1971. Dr. Peleg's current research areas are mathematical and computer-aided modeling and analysis of rheological behaviors of solid foods, mechanical testing of food materials, viscosimetry, powders, particle size distributions, and microbial populations dynamics. Editorial board membership: Journal of Texture Studies (since 1982), Journal of Food Science (1985–1988, since 1999), Journal of Food Process Engineering (1987–1990), Food Science and Technology International (since 1996), Journal of Food Properties (since 1997), Food Engineering Series, Aspen Publishing (since 1998), and Journal of Food Protection (2001–2003). Publication referee (partial list):

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Research proposals referee (partial list): National Science Foundation, Sea Grant, United States

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